



Project Proposal and Feasibility Study

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Derek Bandstra
Willem Both
Sarah Fennema
Joe Westerbeke

Team Advisor: Prof. W. Wentzheimer
Industrial Consultant: Larry A. Hulst, P.E. SECB

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Executive Summary

After the recent earthquake in Haiti, the world was shocked by the dramatic destruction of the buildings in that country. Thousands of people were killed, and millions lost their homes. In response, many aid organizations constructed shelters for displaced Haitian people. The people of Haiti cannot afford to rebuild according to the seismic design practices followed in developed countries. However, for safe, low-cost housing to be a sustainable option for the people of Haiti there needs to be a construction system that does not require financial donations. Using local material, local businesses, and local labor will benefit the local economy and therefore, improve the quality of life in Haiti. The building design must be low-cost, but strong enough to withstand earthquakes or hurricanes.

As a response to this need, the design team Homes for Haiti has determined to design a new building material and simple home design for Haiti. The team has considered many materials, including straw bales, earthbags, bamboo reinforced solid walls, and ferrocement panels. Following research and team discussions related to the focus of the design, the team decided to pursue a ferrocement panel design. A previous design team completed a similar project, and the Homes for Haiti team will work to expand their design to make it more appropriate for the market in Haiti.

The team will accomplish this design through both computer modeling and physical testing. Computer modeling will be completed in Algor. Physical testing will be modeled after the testing completed by the previous design team.

As price is a key constraint of the project, a budget for the current project is included in the following report. A budget and abbreviated business plan are also included for a potential non-profit organization centered on the ferrocement panel design. As the ferrocement panels were chosen, the business plan focused on this design in particular. The overall price of a new home using the ferrocement panels is estimated at \$1200. This cost includes material and labor costs. The average person in Haiti will be able to purchase such a home after about two years based upon a daily income of \$2.

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1 Introduction

On January 12, 2010 an earthquake measuring 7.0 on the Richter scale, along with at least 50 aftershocks, devastated the nation of Haiti on Hispaniola. Estimates placed the death toll at 230,000 and the number of homeless at 1.2 million¹. Many buildings collapsed, including the Presidential Palace, due to inconsistent construction practices. Because Haiti is the poorest country in the western hemisphere, most Haitians cannot afford the building materials and skilled labor required to build an earthquake resistant building that would meet building codes in earthquake zones within developed countries.

Given these circumstances, the project group proposes to develop a low cost building design that would preferably use local materials from Haiti and unskilled labor to construct a small dwelling that can withstand an earthquake of equal magnitude to that which crippled the country. Within this report, the proposed project is described in detail, specifically broken into the management of the project, the research completed, and the design requirements. By the end of the school year, the team hopes to complete a design for a small home using optimized ferrocement panels.

1.1 Course Overview

The project Homes for Haiti is being completed as a Senior Design Project for the Calvin College Engineering Department. The two semester course serves as a capstone for engineering. In the first semester, teams narrow down project ideas through research and design decisions, ending with a statement of feasibility.² In the second semester, the design is refined, ending with a prototype, a design and construction manual, and complete design drawings. This Project Proposal and Feasibility Study is the final report of the first semester.

1.2 Project Overview

As described in the introduction, there is a need for a low-cost, high-strength building component for Haiti. The team has decided to design ferrocement construction panels, using bamboo and bagasse to reinforce and strengthen the concrete. Further description of these materials and the decisions involved are in Design Criteria, Alternatives, and Decisions section. The team will perform materials testing on the ferrocement to determine its strength and other properties. The panel will be tested according to strength and displacement criteria. This builds on the work completed by a senior design team eight years ago³. The other project, Positive Reinforcement, created a building panel using ferrocement reinforced with multiple layers of wire mesh and steel rebar. Though a successful project in terms of meeting strength requirements, the panel designed by Positive Reinforcement was too expensive for the market in Haiti and was overdesigned. The Homes for Haiti team would like to design a panel that minimally meets strength requirements but is lower in cost.

1.3 Introduction to the Team

As pictured in Figure 1, the Homes for Haiti team is composed of four members: Derek Bandstra, Willem Both, Sarah Fennema, and Joe Westerbeke. All team members are senior engineering students in the civil engineering concentration.



Figure 1: Team members: Joe Westerbeke, Willem Both, Derek Bandstra, and Sarah Fennema

Derek Bandstra is from Terrace, British Columbia. He spent the previous summer as an engineering intern for Johann Bunte GmbH in Magdeburg, Germany. Derek is a member of the hockey team at Calvin College. He plans on returning to Canada upon graduation from Calvin and pursuing a Master's degree in Structural Engineering.

Willem Both is from Owen Sound, Ontario. Last summer, Willem worked with Professor Sykes doing engineering research here at Calvin. Willem is a member of the track team at Calvin College. Upon graduation from Calvin, Willem plans on attending the University of Barcelona and then finding a job. His parents were missionaries in Haiti and are good contacts for general knowledge about the country, cultural appropriateness, and finding more contacts that have lived and live in the country currently.

Sarah Fennema is from Brookfield, Wisconsin. Last summer, Sarah worked for RMD Architects designing roof framing systems and drawing buildings in AutoCAD. Sarah runs both cross country and track at Calvin. Upon graduation from Calvin, Sarah plans on pursuing a Master's degree in Structural Engineering.

Joe Westerbeke comes from Oostburg, Wisconsin. During the previous summer, Joe worked at the Christman Company doing construction management for a project downtown Grand Rapids. Upon graduation from Calvin, Joe plans on getting a job in the structural engineering field.

2 Project Management

To achieve the design goals described above, the team must remain focused and motivated throughout the course. The project will be primarily self-managed, with some supervision from the team's advisor Professor Wayne Wentzheimer. Other course instructors are invited to share insight as well.

2.1 Team meetings

Team meetings have occurred twice per week during the first semester but are expected to increase in frequency in the upcoming months. On Tuesday nights, the team has met to discuss action items and work

together on the project. On Friday afternoons, the team has met with Professor Wentzheimer to report progress and adjust the flow of the project. Meeting minutes are taken by Sarah Fennema and recorded in a notebook.

2.2 Document Organization

The team has used Google Docs to share important notes on research and contact lists. A spreadsheet also documents the time spent on the project by each team member. All other files, such as reports, test results, modeling files, and the budget, are in a folder on the Shared drive of the Novell Network, as provided by Calvin College, which can be accessed using Novell Netstorage. In this way, all team members are able to access any file from a computer connected to the internet.

2.3 Team Organization

The following gives a description of the role of each team member.

2.3.1 Derek Bandstra

In the first semester, Derek Bandstra has been in charge of the business plan, transforming the design to a product and service that can be used by local entrepreneurs to implement this design across the country in a sustainable and economical way. Derek is also in charge of the budget, as it is connected to the business plan. In the second semester, Derek will be focused on the connections between the panels and analyzing test results.

2.3.2 Willem Both

Willem Both has contacts in Haiti and elsewhere that he will be in constant conversation with to ensure correct design constraints and feasibility. He will also be working with Joseph create and test finite element analysis (FEA) models for our proposed designs and keeping track of the team's budget. During the second semester, Willem will be focusing on the physical testing of the panels.

2.3.3 Sarah Fennema

Sarah Fennema has been at the head of research, looking for various material options and previous successful and unsuccessful designs. She is also designing spreadsheets to calculate the design wind load and the seismic loading conditions. During the second semester, she will continue her work with the loading conditions, as well as designing the floor plans and roof framing systems for the design of the home.

2.3.4 Joe Westerbeke

Joe Westerbeke will be working with FEA because of his previous knowledge in this area from taking a course in FEA. Using FEA, Joe has been modeling the material on the computer and applying forces in the computer model to ensure the material will not fail. Joe has also served as the project manager, making sure all deadlines are met. During the second semester, Joe will continue his role as project manager and work with Willem on the physical testing of the panels.

2.4 Schedule

The schedule for the project was created in Microsoft Office Project 2007 (see Appendix I for a detailed schedule of tasks).

2.4.1 First Semester

The team's focus during the first semester has been on assessing the feasibility of the project. The major tasks that the team hoped to accomplish are summarized in Table 1.

Table 1: Tasks to be Completed Within the First Semester

Task Name	Deadline Date	Status
Project Proposal Report	9/14	Complete
Selection of Construction Materials	11/30	Complete
Selection of Configuration of Materials	11/30	Complete
Project Website Posted	10/26	Complete
Project Proposal and Feasibility Study Draft	11/18	Complete
Business Plan	12/9	Complete
Project Proposal and Feasibility Study Report	12/9	Complete

2.4.2 Second Semester

The team will be focused on implementing design decisions in the second semester. Several major tasks for the second semester are listed in Table 2.

Table 2: Tasks to be Completed Within the Second Semester

Task Name	Deadline Date
Construction of Sample Ferrocement Panels	2/14
Material Testing on Sample Ferrocement Panels	2/16
Develop Decision Matrix to Choose Optimal Materials	2/28
Perform Structural Analysis Testing on Sample Ferrocement Panels	2/28
Construction of Second Ferrocement Panels	3/8
Design Typical Home	3/22
Create Construction Manual for Panels	3/23
Presentation of Design	(Date Unknown)
Final Design Report Draft	(Date Unknown)

2.5 Budget

Since Willem is the most familiar with the procedures involved with ordering parts, he has been in charge of ordering all materials and will remain in this position. The budget itself will be managed by Derek, since he is the most familiar with the business plan. All major purchasing decisions are discussed with the whole team prior to sending orders.

2.6 Method of Approach

The following section will describe the way in which the team has approached the problem.

2.6.1 Design Methodology

The flow chart seen in Figure 2 portrays the structure of all of the design tasks for the year. Tasks are broken down into “Class Tasks” and “Design Tasks”.

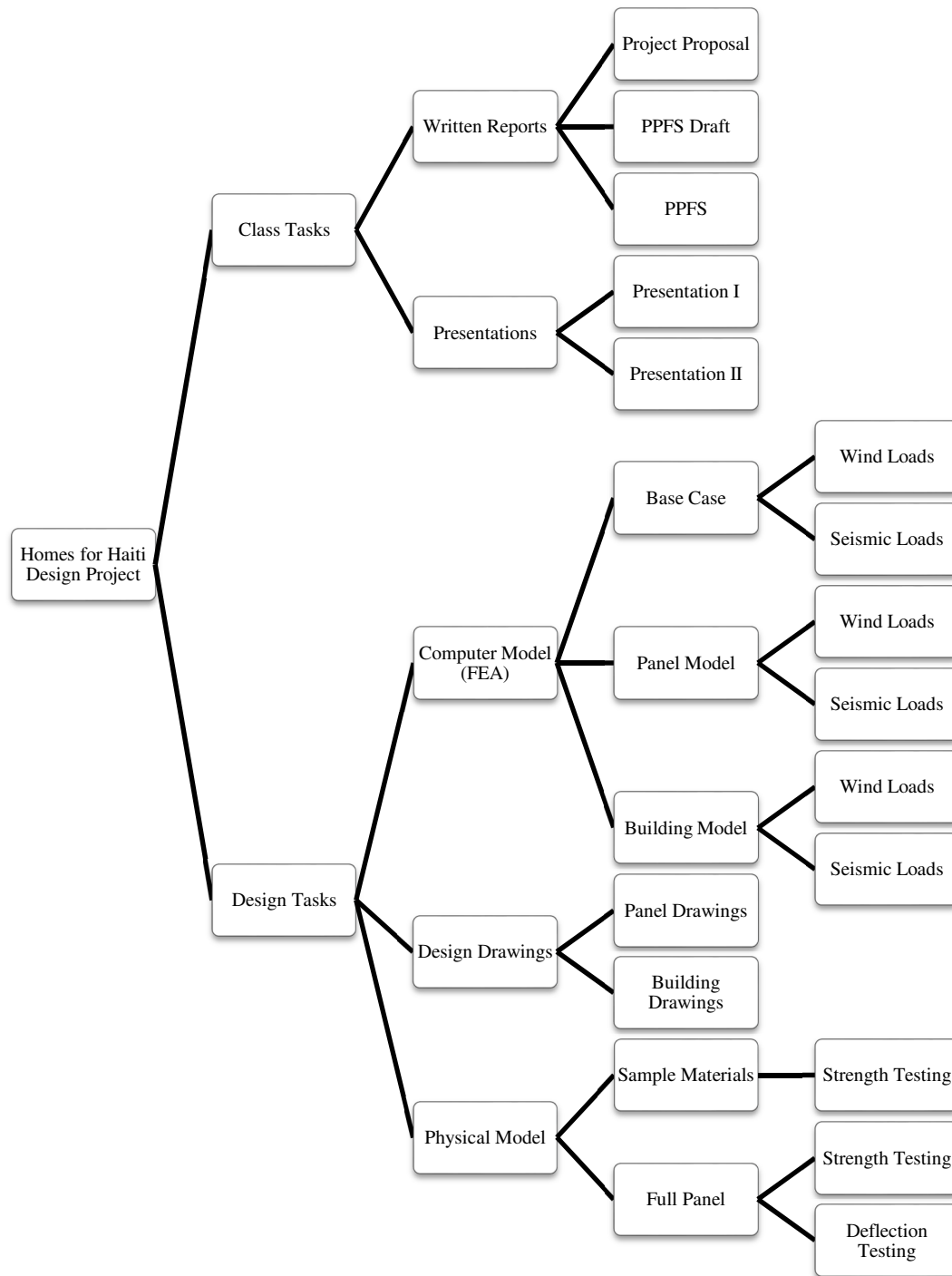


Figure 2: Structure of Tasks for the Design Project

2.6.1.1 Class Tasks

Class tasks will be completed in accordance with the deadlines laid out on the syllabi for Engineering 339 and 340.

2.6.1.2 Design Tasks

2.6.1.2.1 Computer Modeling

The design of the panels will be completed as follows. The computer modeling will involve three main cases. First, a base case computer model has been designed in Algor. The base case has been of the homes that existed in Haiti prior to the 2010 earthquake. The main goal of the base case model is to prove that current construction practices are not adequate and to calibrate the Algor model. Images from the base case model and the wind load calculator are included in Appendix II: Algor, Wind, and Seismic Calculations. All computer models will require both wind and seismic loading conditions. The second case will be a basic panel, reinforced with bagasse and bamboo. The third case will test the whole building structure. As in all tasks of design, iteration will be necessary.

The design drawings for the house will likely be completed at the end of the project. The panel drawings and the building drawings must be detailed enough that an unskilled worker can understand them and could construct a house, but simple enough that an unskilled laborer can understand them. Figure 3 is a preliminary design drawing for the ferrocement panels.

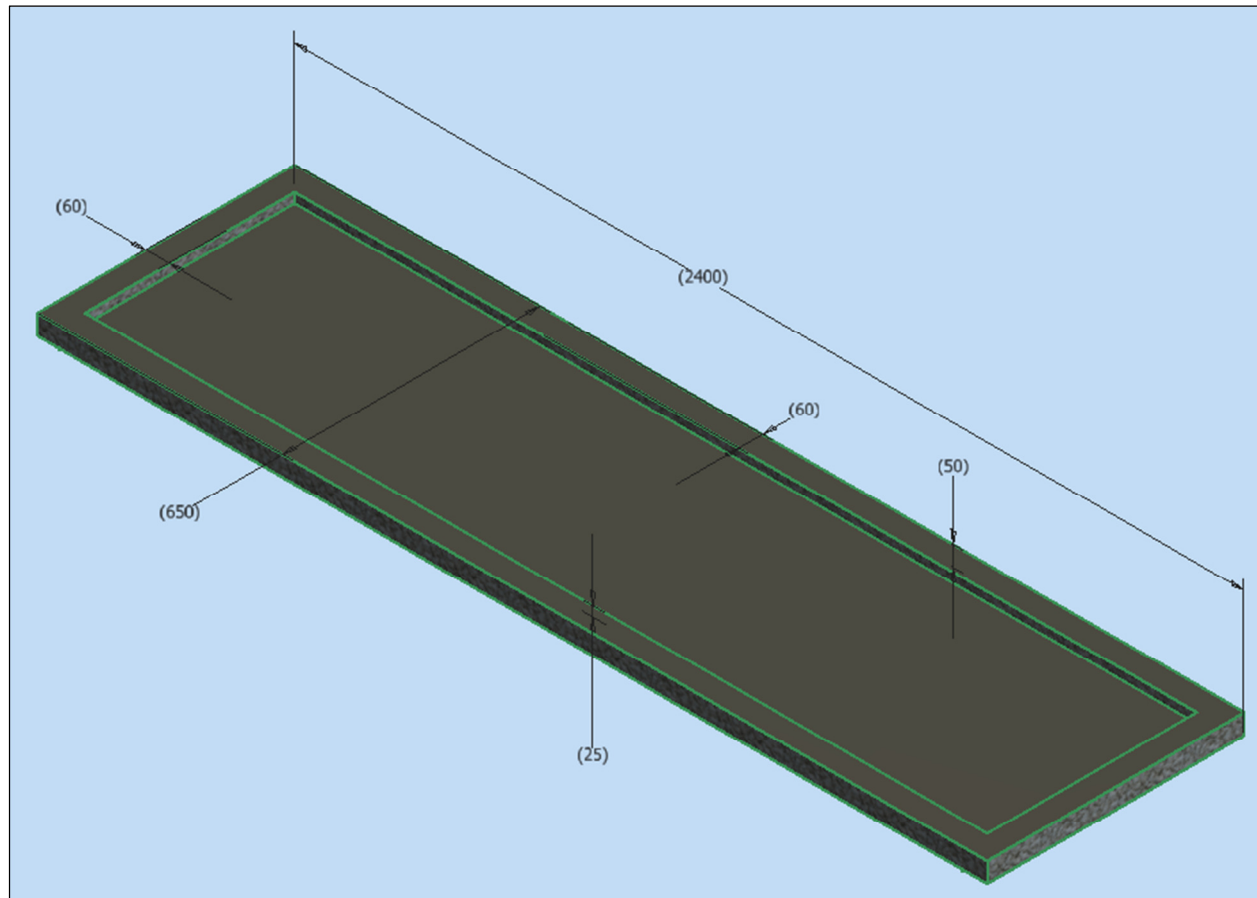


Figure 3: Preliminary Design of Ferrocement Panel (dimensions in millimeters)

2.6.1.2.2 Physical Modeling

The physical modeling of the project will involve strength testing of both the several proposed reinforcing materials and the full panels with these materials. In each case, the additions of bagasse and bamboo will be analyzed to understand the properties of the material. For example, in the sample material testing, a “control sample” will be prepared, using only concrete. In this way, the team will be able to judge

whether or not the bagasse actually helps the strength of the cement. The full panels will be tested for strength, and also tested for deflection. The results of tests completed on the full panels will be compared to those of Positive Reinforcement, the senior design team from 2003⁴. Further description of the testing procedures can be found in the Material Testing Procedures section.

2.6.2 Research Methods

The main research mode was internet searches. While some searches simply utilized tools like Google, the team also used databases such as WorldCat. With the help of librarian Glenn Remelts, the team was able to find a large enough research base to eliminate certain preliminary design options⁵.

2.6.3 Team Communication Methods

The team has been communicating primarily using email. All emails from outside contacts are forwarded to the remaining team members to keep all parties informed.

3 Requirements

3.1 Structural Performance

The main goal for the ferrocement panel is to ensure the individual panel and the structure as a whole do not experience ultimate failure under category 5 hurricane wind loads or seismic loads of a 7.0 magnitude on the Richter Scale. The goal is to have the panels and overall structure strong enough that it will remain upright in these conditions, keeping the residents safe. The owners may need to replace the panels after a severe weather event because of visible cracking, but the panel will remain structurally sound. Even in the developed areas of the world like the United States, a structural engineer's goal is simply to prevent ultimate failure, though often the buildings will need serious renovations to guarantee structural integrity if another extreme event were to occur. Quantitatively, the team targets a panel that meets all U.S. natural disaster codes and standards.

3.2 Cost and Materials

The cost is an important requirement in design to ensure the final design is affordable for residents in Haiti. The team decided to seek a price of \$4.00 per square foot for a 200 square foot building, resulting in a total cost of \$800.00. The team chose the cost of \$800 to be competitive with the current price of homes (approximately \$1,500⁶) while still accounting for overhead costs. The average annual income in Haiti is about \$400, so the overall cost throughout the project is a large issue.⁷

The team requires that the materials be available in the country of Haiti, both to keep the cost down as well as build the Haitian economy. The use of local materials will make the design sustainable as well.

3.3 Cultural Considerations

The design norms of cultural appropriateness and trust are also important constraints. Before the earthquake, homeowners preferred houses that were made completely of concrete, including concrete roofs. During the earthquake, many buildings collapsed, leaving many citizens trapped under concrete roof pieces. This left many Haitians doubting the integrity of these structures and afraid to continue living in homes with concrete roofs. Thus the design must be sensitive to the concerns that post-earthquake citizens of Haiti have. The type of building and the building material also have social status implications. Living in earthen homes would be seen as a reduction of status because concrete homes are more respected.⁸

4 Material Research

We chose four materials that appeared to be feasible construction alternatives for new building designs in Haiti, based on our research and evaluation. The team researched each material extensively, considering strength, material properties, cost, and availability. The team's initial research was not limited to these four materials, though the focus was on these materials because of their building material properties.

4.1 Straw Bale Construction

4.1.1 Background

Baled wheat, oats, barley or rye are the primary materials in a straw bale. These materials are typically waste products, sold by farmers as animal bedding or for landscaping. Construction workers create straw bale houses by stacking the straw bales within a wall, and then applying some sort of stucco as a plaster to ensure the walls are durable, and do not break down with time. People in developing countries as well as developed countries construct straw bale homes, though this construction occurs more often in developing countries because of the price. Many are skeptical about straw bale construction because of moisture issues. Without flooding, the buildings can be extremely durable depending on the type of plaster used. Even if cracks appear in the straw bale walls they are easily repaired with cement or plaster. One source states that the straw will not decompose if cared for correctly, though Dr. Owen Geiger, a team contact on straw bale construction, argues with this. Dr. Geiger, an author, engineer, licensed contractor, and currently a consultant for international housing projects, responded to our questions saying that it is not worth the risk with all the flooding, hurricanes, and earthquakes in Haiti. He said eventually water will find its way into the walls and the house will have to be demolished.⁹

4.1.2 Material Properties

Most material properties are hard to quantify when it comes to straw bales. As compressed pieces of organic material, the modulus elasticity and the yielding stress are difficult to define. One source states that straw bale construction works well in wind speeds up to 50 mph. The material also performed better than a rigid wood-framed wall in earthquake simulations because of its flexibility in earthquake type loading.¹⁰ Though this building method shows potential, we realize that it would be extremely difficult to test and model the straw bales.

4.1.3 Cost and Availability

Straw bales are easy to obtain in Haiti because of the large amount of agricultural land available. Many already build homes of straw bales. Straw bale construction caught on quickly because of its low cost and the ease of construction. The cost and availability of the straw bales makes this construction method appealing, though consideration of the moisture issues is important.

4.2 Earthbag Construction

4.2.1 Background

Earthbag use has been present for many decades, especially for flood control. In construction, a worker fills a bag with some sort of dense material including clay, gravel, soil, or even shells. Often, builders use polypropylene bags because of their cost and availability, though other types of bags are acceptable as well. The main issue in finding a material to use is to make sure the material will not compress after being stacked. Next, a worker stacks the bags in a staggered configuration. The bags can create arches or a dome roof, though some choose to attach their own roof. The arches made of earthbags are appealing to homebuilders because of the simplicity and their lack of need for additional materials. Many add a tin roof because many do not enjoy the aesthetics of the earthbag dome houses. Next, one covers the earthbag walls with some sort of plaster, ranging from earthen plaster, lime plaster, cement stucco, or papercrete. Often builders place pieces of barbed wire between the bags to keep the bags from moving in the case of lateral loading.¹¹

4.2.2 Material Properties

Again, the material properties of earthbags are difficult to quantify, though it is possible. Bryce Callaghan Daigle wrote his thesis on the structural behavior of earthbag housing and put a quantity to some earthbag properties. He tested different size bags for their failure load, the load at which the bag rips, resulting in material loss. For smaller size bags, the resulting average failure load was 360 kN and for larger bags, the resulting average failure load was 700 kN, both of which are acceptable for the loading experienced.¹²

4.2.3 Cost and Availability

Earthbag construction is appealing because of the low material costs. While the materials are inexpensive, there is a large amount of labor needed to create a modest-sized house. Typically, a polypropylene bag costs approximately \$0.11, though one source states the cost in Haiti is closer to \$0.13. Homebuilders ideally use a material that is free and readily available at the site of construction, either gravel or soil. Plaster is also a readily available material that workers easily and economically make or purchase before construction.¹³

4.3 Bamboo Construction

4.3.1 Background

People use bamboo as a construction material all over the world, though usually their use is as actual walls of the building. The U.S. Navy researched the use of bamboo not as an actual wall component, but instead as the reinforcement in concrete. Bamboo has a high tensile stress, and can do an exceptional job at providing necessary tensile reinforcement for the ferrocement panels.¹⁴ There are more than 1,500 species of bamboo, which grow in an assortment of terrains all over the world. In addition, bamboo growth exceeds the growth of most wooden plants, with a top rate of 2 inches per hour and some species growing up to a meter and a half in one day.¹⁵

4.3.2 Material Properties

The structural properties of bamboo can be up to 11 times stronger than steel, though this is measuring the internode, the strongest segment of a piece of bamboo. The strength at the nodes, though, is much lower, and is where the material properties are measured.¹⁶ Figure 4 below shows the different components of bamboo.¹⁷

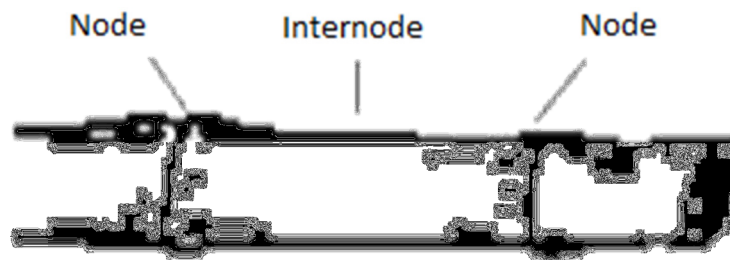


Figure 4: Bamboo Components

The U.S. Naval Civil Engineering Laboratory tests resulted in the following table (Table 3) of bamboo's material properties:

Table 3: Mechanical Properties of Bamboo

Mechanical Property	Symbol	Value (psi)
Ultimate compressive strength		8,000
Allowable compressive stress	σ	4,000
Ultimate tensile strength		18,000
Allowable tensile stress	σ	4,000
Allowable bond stress	u	50
Modulus of elasticity	E	2.5×10^6

Though the source does not state what species of bamboo these properties are for, it does list the following general requirements to ensure the bamboo has these material properties:¹⁸

1. Use only bamboo showing a pronounced brown color. This will insure that the plant is at least three years old.
2. Select the longest large diameter culms available.
3. Do not use whole culms of green, unseasoned bamboo.
4. Avoid bamboo cut in spring or early summer. These culms are generally weaker due to increased fiber moisture content.

Typical grade 40 steel rebar has a minimum yield strength of 40,000 psi and a minimum tensile strength of 70,000 psi. The Modulus of Elasticity of steel is 29,000,000 psi. Although the steel material properties are much higher, the bamboo is less expensive and therefore can be added to the concrete in larger quantities.

4.3.3 Cost and Availability

Bamboo was not available in Haiti until recently. In 1999, Organization for the Rehabilitation of the Environment began bamboo plantations in Haiti. These plantations provide a way to fight against ravine and hillside soil erosion, as well as provide a viable substitute for wood. Another source of bamboo is nearby countries, including Panama and Ecuador. One of the team's contacts, Bruce LeBel, the executive director of World Shelters, provided costs for these countries, which ranged from \$5.00 to \$6.50 for a 3-meter length of bamboo. These costs were current for the first quarter of 2010, though LeBel stated the prices change often. Another contact, Wayne de Jong of the CRWRC, states the local price of bamboo in Haiti as \$25 for a dozen 3-meter lengths. This is much (\$3 or more per culm) less expensive than importing bamboo.

4.4 Bagasse Construction

4.4.1 Background

Bagasse is a natural byproduct of sugarcane production. Bagasse contains 50% fiber, 30% pith, while the remainder consists of moisture or other organic solids.¹⁹ According to the Encyclopedia of the Nations, sugarcane is Haiti's second largest cash crop, after coffee. This makes bagasse, a typically unused material, an especially wise choice as an alternative.²⁰ Mixing the small natural fibers in the concrete panel decreases the amount of micro-cracking possible in the concrete. The fibers allow the concrete to hold together when the panel begins to bend. Another use for this material is bagasse ash. A mixture of sand and 30% to 50% bagasse ash results in a 17% increase in strength for concrete. This is due to the uniform bagasse material filling voids better than the sand.²¹

4.4.2 Material Properties

The material properties of bagasse fiber depend largely on the type of sugar cane plant, its maturity, and the efficiency of the milling plant at removing the pith and other solids. Construction Competence and Consulting provides typical values for a bagasse fiber. A single fiber has an approximate diameter of 0.30 millimeters. The modulus of elasticity ranges from 15 to 19,000,000 MPa, while the ultimate strength ranges from 184 to 290,000 MPa. The team had doubts about how the preservation of natural material in concrete.²² Professor Dornbos, a Calvin College Biology professor, responded to this doubt saying he did not think it would decompose if fully submerged in the concrete panel. A study in Brazil is also testing whether decomposition of bagasse ash occurs within a concrete mixture. While the study is still in progress, preliminary results look promising.²³ While there is plenty of sugarcane being produced, we have not found a definite amount of bagasse that results from Haiti's sugarcane production. A typical panel would only be 2% bagasse, and even if a few hundred homes were built using this material, it would still be an insignificant amount of their total bagasse.

4.4.3 Cost and Availability

There is approximately 2,756,000 hectares in Haiti, and about 12% of this is dedicated to permanent crops, of which 50% is farmable land. While sugarcane is not the country's most profitable crop, it is by far the highest production. In 2009, Haiti produced 1,110,000 metric tonnes of sugarcane, while the next highest sweet potatoes had 271,601 metric tonnes produced. Bagasse is a by-product of sugar cane production, and therefore the source of bagasse in Haiti is exceptionally high. The approximate cost of bagasse is \$10 per cubic meter, so the cost of bagasse per household would be less than 1 dollar.²⁴ The cost and availability of bagasse make this an extremely appealing option for concrete reinforcement in Haiti.²⁵

5 Design Criteria, Alternatives, and Decisions

Because of the nature of the project, the design stage has involved two levels of decisions. First, the team narrowed its focus between four design alternatives, as described in Material Research. The section Initial Design Decisions analyzes these alternatives. Based on the design criteria, the team decided to pursue a ferrocement panel design. Ferrocement Focused Design Alternatives describes design alternatives related to the ferrocement panels themselves.

5.1 Initial Design Decisions

The team developed four design options based on the research previously described. The team chose and weighted design criteria and scored each of the design alternatives, from one to ten, according to the criteria in Table 4.

Table 4: Decision Matrix Between Building Materials

Design Criteria	Ranking	Straw Bales	Earth Bags	Bamboo Reinforced Solid Wall	Ferrocement Panels
Feasibility	40%	1	2	4	8
Cultural Appropriateness	10%	4	1	6	6
Trust	10%	2	6	8	5
Estimated Material/ Equipment Cost	20%	6	10	5	5
Ease of Construction	10%	2	10	1	6
Ease of Testing/ Modeling	10%	1	0	7	7
Total Score	100%	2.5	4.5	4.8	6.6

The team assigned weights to each design criteria according to importance. The score given to each alternative was based on comparison to all materials, not just the four considered. The following paragraphs explain each criterion in detail, and tables justify the scores assigned to each design alternative.

5.1.1 Feasibility

This criterion comes from group discussions and opinions about the appeal and practicality of an alternative. This criterion included the difficulty of physical construction for testing purposes, the appeal of continuing work from the 2003 design team, the conduciveness to applying engineering principles, the difficulty level of the design, and the possibility of creating an innovative product. The team weighted this criterion the highest because it is multi-faceted and directly affects the interest and drive of the team members and therefore the quality of work.

Table 5 shows the justification for the scores of each alternative.

Table 5: Justification of Scores for Design Alternatives (Feasibility)

Design Alternative	Justification of Score
Straw Bales	Have been designed already, not many engineering principles to apply
Earth Bags	Have been designed already, not many engineering principles to apply
Bamboo Reinforced Solid Wall	Have been designed already
Ferrocement Panels	Most interesting to construct and test, able to optimize work completed by Positive Reinforcement, innovative combination of materials

5.1.2 Cultural Appropriateness

The culture of Haiti is much different than in the United States and so special research and considerations must be made to ensure that the design chosen is acceptable. Using helpful information from Willem's parents, the team rated the cultural appropriateness of each alternative as seen in Table 6 below.

Table 6: Justification of Scores for Design Alternatives (Cultural Appropriateness)

Design Alternative	Justification of Score
Straw Bales	Not a status symbol like a concrete home, unknown whether this would be acceptable because it is not used in Haiti
Earth Bags	Living in an earthen home seen as a lower social status by the Haitian people ²⁶
Bamboo Reinforced Solid Wall	Concrete homes are status symbols
Ferrocement Panels	Concrete homes are status symbols

5.1.3 Trust

Since the 2010 earthquake, Haitians are hesitant to trust concrete above their heads.²⁷ This restricts the home being made entirely of panels as Positive Reinforcement had designed.²⁸ They still prefer the concrete walls so if concrete is chosen it would be limited to walls. The fear of cement falling down on them is the first consideration for this design criterion. It also covers climate considerations, as the people of Haiti must trust that the design can endure seasonal climates, especially the rainy season. Table 7 describes both considerations for each alternative.

Table 7: Justification of scores for design alternatives (Trust)

Design Alternative	Justification of Score
Straw Bales	Not trustworthy during the rainy season due to mold issues ²⁹
Earth Bags	Trusted for strength
Bamboo Reinforced Solid Wall	Design trusted because concrete does not extend above heads of humans
Ferrocement Panels	Not as trustworthy because concrete at full height, but sectional nature gives impression of weak points

5.1.4 Estimated Material Cost

The team estimated material costs considered for this criterion from research and comparisons between Haiti and countries with a similar climate and level of development. Larry Hulst gave us general cost comparison estimates of the main components from each option.³⁰ Table 8 describes the scores for each design alternative.

Table 8: Justification of Scores for Design Alternatives (Estimated Material Cost)

Design Alternative	Justification of Score
Straw Bales	Material is inexpensive, but cost of labor higher
Earth Bags	Material is inexpensive and readily available
Bamboo Reinforced Solid Wall	Bamboo is less expensive than steel rebar, but requires cost of cement and bamboo
Ferrocement Panels	Bamboo is less expensive than steel rebar, but requires cost of cement, bagasse, and bamboo

5.1.5 Ease of Construction

This includes estimated time and skill required to construct an entire home. Varying levels of skill and time can produce varying performance for straw bales³¹ and earthbags³². It was estimated what amount of skill and time would be required to produce a home that would meet our design goals. The team ranked design alternatives according to the justifications seen in [Table 9](#).

Table 9: Justification of Scores for Design Alternatives (Ease of Construction)

Design Alternative	Justification of Score
Straw Bales	Requires skill
Earth Bags	Skill level varies depending on design, but taken as low
Bamboo Reinforced Solid Wall	Extremely difficult to pour concrete, difficult to make large forms, concerns about concrete consistency
Ferrocement Panels	Made on- or offsite, single batch of concrete makes one panel, repetitive nature would increase production, skill required to attach panels to each other, the foundation, and the roof elements

5.1.6 Ease of Testing

Western Michigan University has offered to allow testing of concrete samples. The team will also replicate the simple test that Positive Reinforcement did using sand bags.³³ For straw and earth bags it would very difficult to test and quantify the strength without building full scale and testing on large shake tables. Shake tables are difficult to be scheduled in because they are in such high demand.³⁴ In addition, being able to test the material on a smaller scale is desirable to reduce testing materials' costs. The ability to model accurately how the material would respond to stresses would also be advantageous. [Table 10](#) explains the ratings of each design alternative in this category.

Table 10: Justification of Scores for Design Alternatives (Ease of Testing)

Design Alternative	Justification of Score
Straw Bales	Difficult to test response of material to moisture, difficult to model in Algor
Earth Bags	Would require earthquake simulator for testing, difficult to model in Algor
Bamboo Reinforced Solid Wall	Difficult to test small samples, able to model in Algor
Ferrocement Panels	Easy to test small samples, able to model panels in Algor, difficult to model connections

5.2 Ferrocement Focused Design Alternatives

Based on the decision matrix in Initial Design Decisions, the team has focused on a ferrocement design. There are several alternatives within the ferrocement panel design. Because a major part of this project will be testing and comparing different combinations of these design alternatives, the team cannot make design decisions based solely on ranked criteria. Instead, design decisions will be informed by computer modeling as well as physical construction and testing. The four design components are concrete, tensile reinforcement, wire mesh, and discontinuous fibers. The final design could include any of several combinations of these components. The team will assess each component according to its necessity for the strength of the overall design and its cost.

5.2.1 Concrete

In 2003, Positive Reinforcement did a lot of work to maximize their strength of concrete with different ratios of sand, cement, and water³⁵. Instead of retesting different ratios of sand, cement, and water, the team will verify the optimal recipe from the previous team. Since the previous design team documented the process of creating the optimal recipe and test results, the current team will trust their optimal recipe.

The team is considering supplementing this optimal recipe with additives for the concrete design component. One such additive is bagasse ash, as described in Material Research. Since other additives are not locally available in Haiti, the team is not considering other additives.

5.2.2 Tensile Reinforcement

Bamboo is one option to replace steel rebar to cut down on cost and use local materials. Bamboo has high tensile strength and an increasing presence in Haiti. Ninety-eight percent of the country's forests have been cut down so wood is imported and expensive.³⁶ As bamboo increases in popularity as an erosion control measure, it will increasingly become the economical choice for tensile reinforcement in concrete.

Steel rebar is the other major option for the tensile reinforcement design component. Bamboo is slightly less expensive than rebar.³⁷ However, this decision will also consider the fact that any steel must be imported, while bamboo is available from Haiti. As one goal for the design is sustainability and accessibility, the importation of a key design component could be a deciding factor.

5.2.3 Mesh

Positive Reinforcement did not test chicken wire mesh because it does not help with tensile forces as much as square wire mesh, despite being a quarter of the price.³⁸

The team will compare square wire mesh to the chicken wire mesh. Positive Reinforcement used four layers of square wire mesh in their panel, which was overdesigned, so decreasing the number of layers is also an option that could provide the required strength at a reduced cost.

Woven bamboo will also be considered but would require quite a lot of work and certainly only one mesh layer would be included in every panel.

5.2.4 Discontinuous Fibers

Bagasse and short steel wires have been proven to decrease micro-cracking within concrete, and both will be tested. The effect of both on our dimensions is unknown.

6 Material Testing

The three major tests for the concrete panel to determine mechanical properties are compression strength, tensile, and bending. American Society for Testing of Materials standardizes these tests. The team will run these secondary tests as well:

- Testing the physical, chemical and mechanical properties of the component materials (water purity, sieve analysis of aggregate, strength of mesh, etc.)
- Tests to control the properties of the fresh mortar mix (slump, air content, etc.)
- Secondary mechanical properties (cracking, fatigue, permeability, durability)³⁹

6.1 Material Testing Procedures

Calvin College has a compression testing machine that is used every year for ENGR 106 that the team will be utilizing. Tensile test and moment test machines, however, need to be found elsewhere. Western Michigan University has agreed to have us visit and decide what testing machines we would like to use for next semester. This will include the tensile test and the moment test machine if they are available.

Careful design and construction of the specimens is critical so the panel properties corresponding with the results can be trusted. Using the same mesh inside the panel and the scale-downed specimen may affect the transferability of the results from the specimen to the panel's properties. This may especially be true for a mesh with large openings because the specimen will have small numbers of repeated patterns. The specimen, therefore, may yield prematurely because it does not constitute a matrix as the same mesh would in a full sized panel. Our results will also be verified by Positive Reinforcement's results for both compression and moment testing and results found in Naaman Chapter 7.⁴⁰

To minimize the number of tests that need to be run at Western Michigan University, a number of combinations have been decided upon. Testing a certain material's effect such as the addition of bagasse ash in concrete on the concrete's properties will decide whether the material will be included. It is also of interest how different materials interact with each other such as bagasse and mesh. The overall strength gained from using materials in conjunction as opposed to using only one such as mesh and rebar must also be investigated. Below is the list of combinations of materials added to concrete. This list will determine individual contributions to properties and combined contributions to quantify every possible design.

1. Bagasse
2. Mesh
3. Bamboo
4. Rebar
5. Bagasse Ash

6. Mesh and Bamboo
7. Mesh, Bamboo and Bagasse

The testing specifications and specimen sizing will be determined during the visit to Western Michigan University.

The team will also need to determine the strength of the ferrocement using rebar used in Haiti compared to rebar used in the United States. Results from tests of ferrocement specimens using US rebar will need to be modeled in Algor. By changing the strength of the ferrocement using strength ratios of US to Haiti rebar a new overall strength will be estimated.

7 Computer Testing

The team created a base case design of a typical Haitian house in Autodesk Algor. The team used the base case to ensure the calculated wind and earthquake forces are correct, and resulted in a typical pre-earthquake Haitian house collapsing, with stresses greater than the materials' ultimate strength. The yield strength of the concrete used in the Algor model is assumed to be approximately 1,300 psi, so failure of the wall will result with any stresses greater than this.

7.1 Computer Testing Procedures

The base model building consists of concrete blocks 8" by 8" by 16" which creates a 10' by 20' building with 8' tall walls. Because the material properties of the concrete block and the mortar are similar, the team modeled the building using continuous concrete walls. There are different bonding strengths of the mortar to the block, but to simplify our model we will assume this interface is not the weakest point. Another issue the team faced is the fact that a concrete block has two holes through the center, which can be seen in the figure below.⁴¹



Figure 5: Typical Concrete Block

To model the two holes in the concrete block in Algor would be very difficult. To ensure the accuracy of the model, the team calculated an equivalent width of the wall to be 7.8" instead of the 8" wide wall. These calculations use the moment of inertias of the concrete block and found an equivalent solid wall width. These calculations can be seen in Appendix 3. The concrete used in Haiti does not meet the standard concrete properties that Algor offers. The team calculated an approximate equivalent concrete modulus of elasticity using the following equation:

$$E = 33 \cdot w_c^{1.5} \cdot \sqrt{f'_c} \quad \text{Equation 1}$$

Where w_c is the weight of concrete in pound per cubic foot and f'_c is the compressive strength of concrete at 28 days in pounds per square inch.⁴² One source stated that the Haitian-made concrete had an average compressive strength of 1,300 psi, while a separate source stated that the average weight of the concrete was an eighth that of the weight use in the United States, which is approximately 145 lbs./ft³. The calculation resulted in a modulus of elasticity of 13,220,000 lbs./ft² which is significantly smaller than concrete's normal modulus of elasticity, which is approximately 524,800,000 lbs./ft².^{43 44}

The team also calculated a new shear modulus for the concrete, using the following equation:

$$G = \frac{E}{2(1 + \nu)} \quad \text{Equation 2}$$

where E is the modulus of elasticity and ν is Poisson's ratio for concrete, which is approximately 0.15.⁴⁵

The model also consisted of a fixed boundary condition along the bottom of the wall, rather than a pinned boundary condition, which most closely resembles the interaction between the concrete block and concrete foundation. The calculations done for the computer modeling can be seen in Appendix 3. The Algor model can be seen in **Figure 6** below. The values of the force vectors were simply changed for different loading situations.

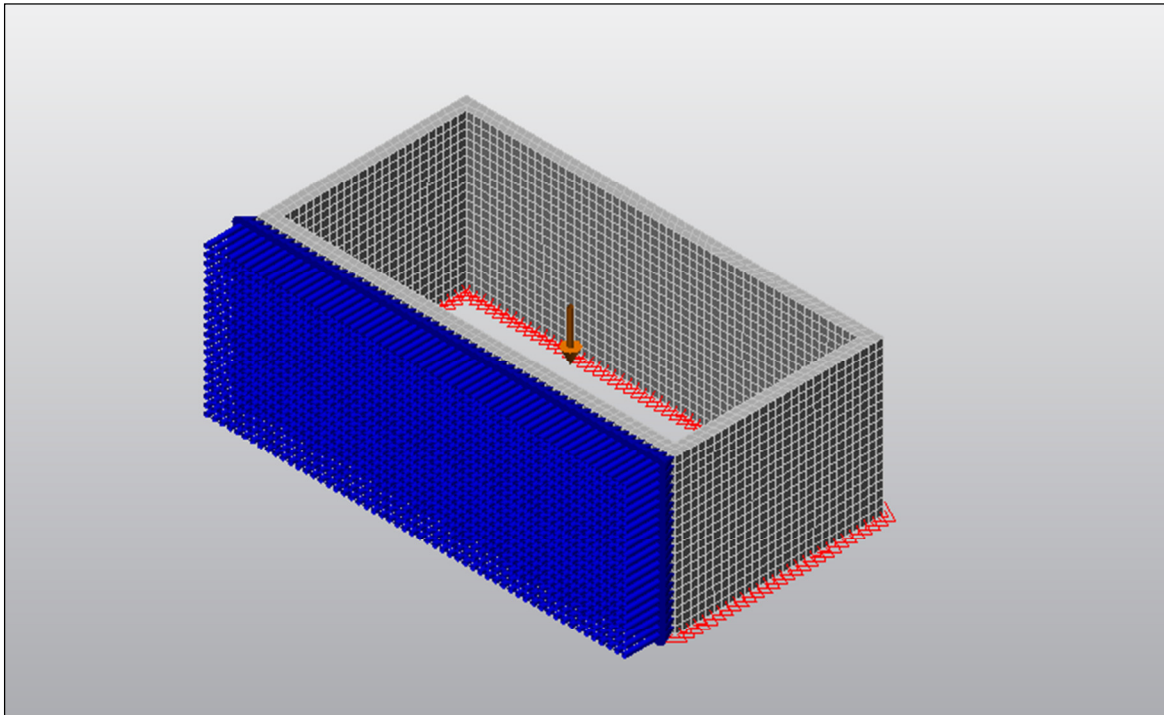


Figure 6: Base Case Model

The team used an American Society of Civil Engineers Code book to calculate the design forces for wind and earthquake loads. A category 5 hurricane resulted in a pressure of 80.8 pounds per square foot.

7.1.1 Hurricane Load Calculations

The main concern for hurricane loading is the wind speed of the hurricane. Based on the ASCE 7 Code, the design wind speeds chosen were the same as wind speeds seen in Florida during hurricanes. An Excel spreadsheet was developed to compute the load seen by a structure with a basic wind gust speed of 200 mph. The basic approach used the wind speed to calculate a pressure on the side of the structure, which could then be modeled as a force in Algor. The wind load calculations assumed that the building was located in a relatively densely populated area, and that the building was not situated on a hill. Dimensions used were those of a typical building in Haiti.

7.1.2 Earthquake Load Calculations

Earthquake loads were calculated based on the short period acceleration of the ground from the 2010 earthquake based on data from the USGS website⁴⁶. The basic design principle uses the ground acceleration to create a coefficient, which when multiplied by the total weight of the building, yields the shear force seen at the base of the building. Again, all calculations were completed using the ASCE 7 Code.

7.2 Computer Testing Results

The hurricane loading resulted in a stress of 137.4 psi. The compressive strength of our specified concrete is 1,300 psi of the specified concrete, while the tensile strength is typically 15% of the compressive strength, resulting in a tensile strength of 195 psi. The resulting loading from hurricane type winds does not exceed the tensile or compressive strengths, showing that the concrete building is safe under a category 5 hurricane. This result is exactly what the team expected, since the larger concrete walls should hold up against a wind loading. The Algor modeling results can be seen in Figure 7 below.

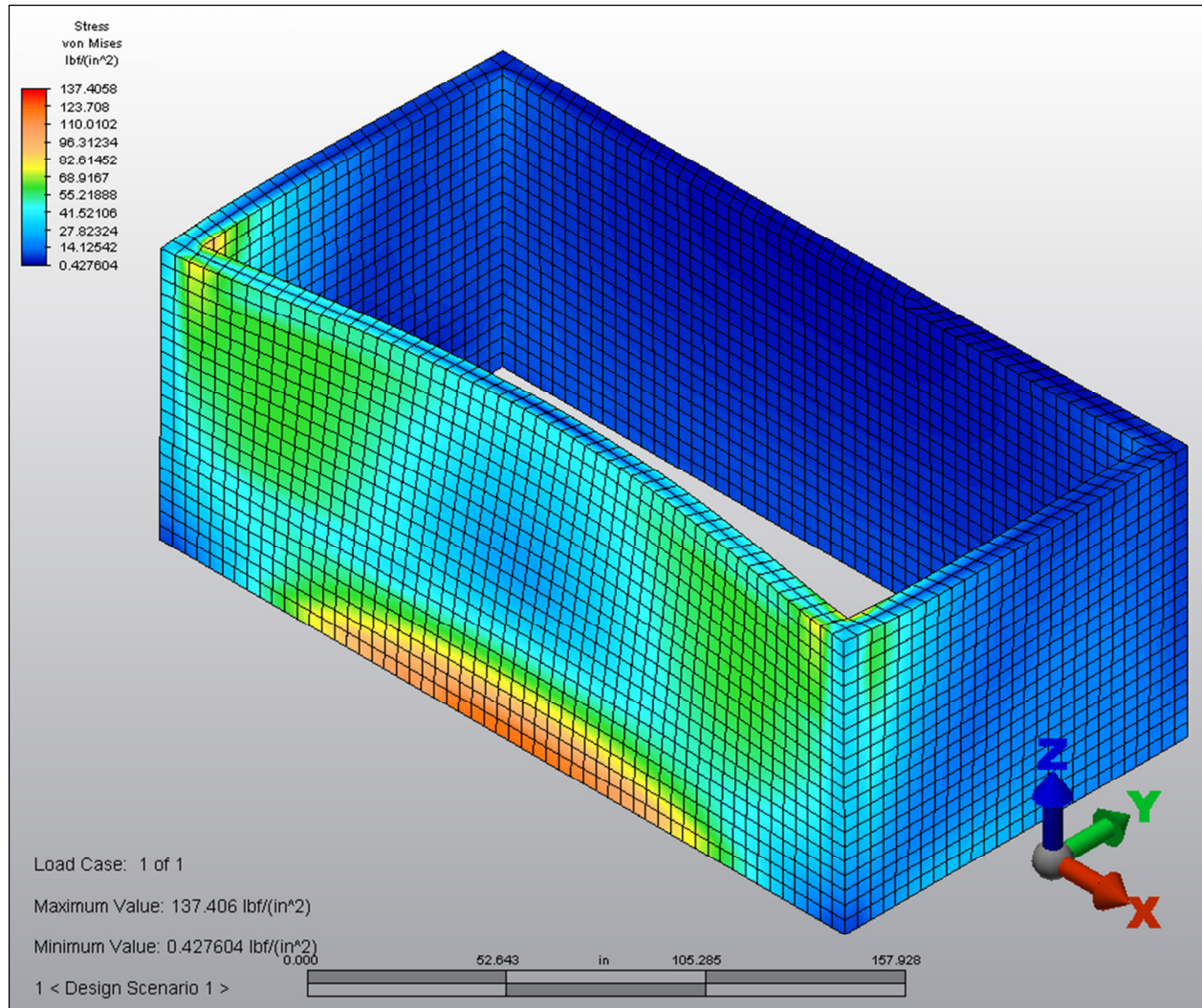


Figure 7: Base Case Results for Hurricane Loading

The earthquake loading resulted in a stress of 2,090 psi, which is larger than both the compressive and tensile strengths, resulting in a failure of the concrete by both failure methods. The team expected this result, since earthquake loading depends heavily on the mass of the building, and this completely concrete building is heavy. The results can be seen in [Figure 8](#) below.

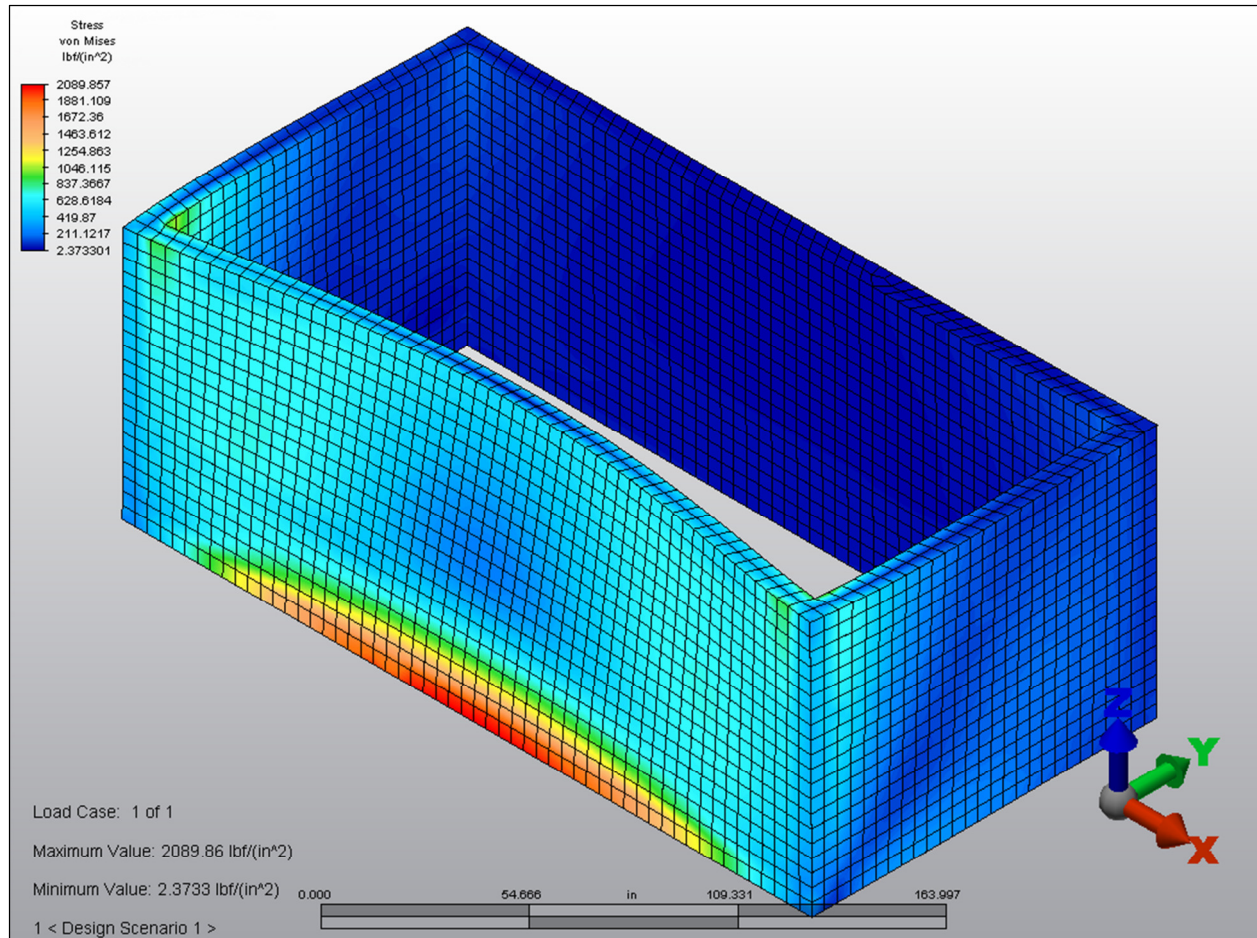


Figure 8: Base Case Results for Earthquake Loading

8 Abbreviated Business Plan

8.1 Development

Development costs for this project include the cost of supplies: bamboo, bagasse, concrete, low-grade wood for the forms, wire mesh, and for travel to and from Western Michigan University (WMU) for testing of some of our samples. There is also potential for cost in regards to WMU testing for travel and the testing itself.

Funding for the development of the prototype will come from the remainder of the team budget from Calvin College. The team formally requested a budget of \$300 from the College to cover the expenses incurred and the college granted a budget of \$400 to allow for contingencies. The bagasse is free of charge because the Calvin College Biology department has an excess that the team is able to use. The concrete is free of charge from the Calvin College Engineering department, who has a large quantity in storage for use by a 100-level Engineering class.

Table 11: Development Budget Timeline

	Bamboo	Bagasse	Concrete	Wooden Forms	Wire Mesh	Haiti Travel	Budget	Innotec Grant
November	\$(250.00)	Donated	Donated	\$(40.00)	\$(40.00)	\$(2,500)	\$300.00	\$2,500
December	\$(250.00)	Donated	Donated	\$(40.00)	\$(40.00)	-	\$400.00	-

Above in **Table 11**, the local cost of bamboo in the United States is \$250, including shipping and handling, and the cost for wood for forms is an estimated \$40. Within the team's testing, a comparison of small panels with and without the mesh, steel rebar versus bamboo, and bagasse versus no bagasse will require an estimated \$40 worth of the wire mesh. The team looked at travel to Haiti, but upon not receiving any external funding, such as through the Innotec Grant, the team decided not to fly down to Haiti.

8.2 Production

For the production of a house made from the panels that result from the team's design, the team calculated costs based upon material prices provided by Wayne de Jong.⁴⁷ The direct production costs are in **Table 12**. The bagasse cost in **Table 12** is included at this point because the team considers it a design additive in the ferrocement panel, but until the team tests and analyzes the panels with the bagasse, an exact quantity per panel cannot be determined.

Table 12: Production and Construction Cost Estimate per Home in Haiti

	Bamboo	Cement	Sand	Bagasse	Labor	Total Est. Cost
November	\$40	\$200	\$12.00	\$15/1000kg	\$450	\$700.00
December	\$130	\$200	\$12.00	\$10/m ³	\$200	\$550.00

The bamboo cost is from a dozen dry pieces of about 3 meters in length and for each building, made of 30 panels, requires 183 meters or 61 pieces of bamboo. The cement cost comes from using 42.5-kilogram bags of cement. Each bag costs \$7.50 and produces 1.164 panels. The sand cost comes from a desired 1:2:2 concrete mixture (water : cement : sand), based upon the same volumetric requirement as cement per panel. The cost of sand in Haiti is \$16.25 per cubic meter. The costs for cement and sand are from a 'Cost of Construction Materials' pdf that provides "typical CMU (Concrete Masonry Unit) construction estimates in St. Marc, Haiti."⁴⁸ The cost of labor is for four unskilled workers at a rate of \$2 (compared to the November estimate of \$6.25) per day and an unskilled labor supervisor working at a rate of \$8 per day (compared to the November estimate of \$11.25). The cost of labor is from the conversation that took place between the team and Larry Hulst.⁴⁹

8.3 Production and Implementation

The end goal for this design is to create a repeatable model for Haitians to build themselves. Part of the marketing process is imbedded in the implementation of our design, as we will create a basic enough manual and construction process that unskilled laborers can build a functioning and structurally sound home under the supervision of a single knowledgeable worker. This would create accountability for doing it right and would create a process that Haitians can take pride in, having used their own materials to create homes for themselves. The product that will go to Haiti will be the manual, using their terminology and is in Haitian Creole, their native tongue. The specifics within the manual, the actual procedure recommended, will be trialed during the second semester when the team creates sample panels to

maximize simplicity. This manual will be included in the final design report. Their terminology will include substituting official measurements for concrete mixing with a basic unit, such as replacing gallons with shovels or buckets.

9 Conclusion

Based upon the current model, the team has been able to create a possible home for the cost of \$1200. This number, however, is going to change as we learn more accurate, local and recent costs for the material used and for labor. There are also overhead costs that cannot be determined at this stage of the design as the scale at which in country production will occur is yet to be determined. There is also the possibility that some of the major points of our design will change, such as the primary reinforcement. The final scope of the project is determined at the beginning of the spring semester, when the panel design nears completion. As of right now, with the current \$1200 home (after accounting for foundation, roofing and overhead costs), the feasibility of a sustainable model is very good, as homes can cost in the area of \$2700, such as from the CRWRC. This is of sufficiently low cost that allows more people to get proper housing faster and still be confident that their dwelling is safe.

¹ Rodgers, Lucy. "Why did so many people die in Haiti's quake?" BBC News 14 Feb. 2010. Web.

² Bandstra, Derek. *Homes for Haiti: Team 13*. Ed. Willem Both, Sarah Fennema, and Joe Westerbeke. Calvin College, 14 Oct. 2010. Web. 4 Dec. 2011. <<http://www.calvin.edu/academic/engineering/2011-12-team13/>>.

³ Van Der Puy, Joe, Adam Peterson, Steve Oosting, and Eric Klompmaker. *Positive Reinforcement*. Final Report ed. Grand Rapids: Calvin College, 2003. N. pag. Print.

⁴ Van Der Puy, Joe, Adam Peterson, Steve Oosting, and Eric Klompmaker. *Positive Reinforcement*. Final Report ed. Grand Rapids: Calvin College, 2003. N. pag. Print.

⁵ Remelts, Glenn. Personal interview. 13 Oct. 2011.

⁶ Hulst, Larry. Personal interview. 16 Nov. 2011.

⁷ "Haiti." US Aid, 2004. Web. 13 Oct. 2011. <http://www.usaid.gov/policy/budget/cbj2004/latin_america_caribbean/haiti.pdf>.

⁸ Both, Mary M. Personal interview. 10 Oct. 2011.

⁹ *Straw Bale Construction*. Sustainable Sources, 2011. Web. 19 Sept. 2011. <<http://strawbale.sustainablesources.com/>>.

¹⁰ *Straw Bale Construction FAQ's*. California Strawbuilding Association, 2010. Web. 20 Sept. 2011. <<http://www.strawbuilding.org/sbweb/content/strawbale-codes>>.

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- ¹¹ Hart, Kelly, and Dr. Owen Geiger. *Earthbag Building*. Green Home Building, n.d. Web. 23 Sept. 2011. <<http://www.earthbagbuilding.com/index.htm>>.
- ¹² Callaghan Daigle, Bryce. "Earthbag Housing: Structural Behaviour and Applicability in Developing Countries." (2008). Web.
- ¹³ Hart, Kelly, and Dr. Owen Geiger. *Earthbag Building*. Green Home Building, n.d. Web. 23 Sept. 2011. <<http://www.earthbagbuilding.com/index.htm>>.
- ¹⁴ Brink, Francis E., and Paul J. Rush. "Bamboo Reinforced Concrete Construction." US Naval Civil Engineering Laboratory, Feb. 1966. Web. 20 Sept. 2011. http://www.romanconcrete.com/docs/bamboo1966/BambooReinforcedConcreteFeb1966.htm#_Toc501122823
- ¹⁵ "Why Bamboo?" Environmental Bamboo Foundation, n.d. Web. 4 Oct. 2011. <<http://www.bamboocentral.org/whybamboo.html>>.
- ¹⁶ "Bamboo - Stronger Than Steel?" Bamboo Fencer, 23 Mar. 2010. Web. 2 Oct. 2011. <<http://blog.bamboofencer.com/bamboo-poles/bamboo-stronger-than-steel-really/>>.
- ¹⁷ "Growing Bamboo." Tearfund International Learning Zone, 10 Aug. 2005. Web. 14 Nov. 2011. <<http://tilz.tearfund.org/Publications/Footsteps+21-30/Footsteps+23/Growing+bamboo.htm>>.
- ¹⁸ Brink, Francis E., and Paul J. Rush. "Bamboo Reinforced Concrete Construction." US Naval Civil Engineering Laboratory, Feb. 1966. Web. 20 Sept. 2011. <http://www.romanconcrete.com/docs/bamboo1966/BambooReinforcedConcreteFeb1966.htm#_Toc501122823>.
- ¹⁹ "Natural Fiber Reinforced Concrete." *Construction Competence & Consulting*. N.p., n.d. Web. 22 Sept. 2011. <<http://www.3-co.com/Pro/Principles/Special%20Concrete/nfrc.htm>>.
- ²⁰ "Haiti - Agriculture." *Encyclopedia of the Nations*. N.p., 2008. Web. 6 Nov. 2011. <<http://www.nationsencyclopedia.com/Americas/Haiti-AGRICULTURE.html>>.
- ²¹ Selvanayagam, Ruban. "Brazil Getting Ready to Make Stronger and Cheaper Concrete with Bagasse." *Brazzil*. N.p., 22 Sept. 2010. Web. 8 Nov. 2011. <<http://www.brazzil.com/articles/224-september-2010/10430-brazil-getting-ready-to-make-stronger-and-cheaper-concrete-with-bagasse.html>>.
- ²² "Natural Fiber Reinforced Concrete." *Construction Competence & Consulting*. N.p., n.d. Web. 22 Sept. 2011. <<http://www.3-co.com/Pro/Principles/Special%20Concrete/nfrc.htm>>.

-
- ²³ Selvanayagam, Ruban. "Brazil Getting Ready to Make Stronger and Cheaper Concrete with Bagasse." *Brazzil*. N.p., 22 Sept. 2010. Web. 8 Nov. 2011. <<http://www.brazzil.com/articles/224-september-2010/10430-brazil-getting-ready-to-make-stronger-and-cheaper-concrete-with-bagasse.html>>.
- ²⁴ Paturau, J.M. "Alternative Uses of Sugarcane and Its Byproducts in Agroindustries." Food and Agriculture Organization, n.d. Web. 18 Oct. 2011. <<http://www.fao.org/docrep/003/s8850e/S8850E03.htm>>.
- ²⁵ "Haiti." Food and Agriculture Organization, 8 July 2011. Web. 19 Oct. 2011. <<http://www.fao.org/countries/55528/fr/hti/>>.
- ²⁶ Both, 10 Oct 2011
- ²⁷ Hulst, Larry. Personal interview. 17 Nov. 2011.
- ²⁸ Van Der Puy, Joe, Adam Peterson, Steve Oosting, and Eric Klompmaker. *Positive Reinforcement*. Final Report ed. Grand Rapids: Calvin College, 2003. N. pag. Print.
- ²⁹ Hulst, Larry. "Industrial Consultant." Message to Joe Westerbeke. 4 Oct. 2011. Web.
- ³⁰ Hulst, Larry. "Industrial Consultant." Message to Joe Westerbeke. 4 Oct. 2011. Web.
- ³¹ *Pakistan Straw Bale and Appropriate Building*. N.p., n.d. Web. 4 Oct. 2011. <<http://www.paksbab.org/html/index.php?id=1>>.
- ³² Arieff, Allison. "Rebuilding in Haiti." *Opinionator*. The New York Times, 10 Apr. 2010. Web. 6 Dec. 2011.
- ³³ Van Der Puy, Joe, Adam Peterson, Steve Oosting, and Eric Klompmaker. *Positive Reinforcement*. Final Report ed. Grand Rapids: Calvin College, 2003. N. pag. Print.
- ³⁴ DeRooy, Leonard. Personal interview. 23 Sept. 2011.
- ³⁵ Van Der Puy, Joe, Adam Peterson, Steve Oosting, and Eric Klompmaker. *Positive Reinforcement*. Final Report ed. Grand Rapids: Calvin College, 2003. N. pag. Print.
- ³⁶ Hulst, 17 Nov 2011
- ³⁷ Hulst, 17 Nov 2011
- ³⁸ Van Der Puy, Joe, Adam Peterson, Steve Oosting, and Eric Klompmaker. *Positive Reinforcement*. Final Report ed. Grand Rapids: Calvin College, 2003. N. pag. Print.

³⁹ Naaman, Antoine E. *Ferrocement & Laminated Cementitious Composites*. Ann Arbor: Techno Press 3000, 2000. 1-273. Print.

⁴⁰ Naaman, Antoine E. *Ferrocement & Laminated Cementitious Composites*. Ann Arbor: Techno Press 3000, 2000. 1-273. Print.

⁴¹ *Cinder Block*. LoveToKnow, Corp., Burlingame, CA. *Google*. Web. 4 Dec. 2011.

⁴² American Concrete Institute. ACI Committee 318 (2008). *ACI 318-08: Building Code Requirements for Structural Concrete and Commentary*.

⁴³ Lafsky, Melissa. "Earthquakes Don't Kill People...Bad Buildings Do': More on Haiti's Building Codes." *The Infrastructurist: America Under Construction*. N.p., 20 Jan. 2010. Web. 12 Nov. 2011.

⁴⁴ "Recycling Haiti's Earthquake Rubble Into Safe, Strong Concrete." Environment News Service, 6 Jan. 2011. Web. 5 Nov. 2011. <<http://www.ens-newswire.com/ens/jan2011/2011-01-06-01.html>>.

⁴⁵ Riley, William, Leroy Sturges, and Don Morris. *Mechanics of Materials*. 6th ed. Hoboken, NJ: John Wiley & Sons, Inc., 2007. Print.

⁴⁶ "Shakemap us2010rja6." *USGS: science for a changing world*. United States Geological Survey, 4 Mar. 2010. Web. 20 Nov. 2011. <http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/2010rja6/#0.3_sec_Period>.

⁴⁷ de Jong, Wayne. "RE: Haitian Research for Calvin Students." Message to By Derek Bandstra and Glenn Remelts. 21 Nov. 2011. E-mail.

⁴⁸ "I.7 Cost of Construction Materials." Archive Global. N.p., n.d. Web. 10 Nov. 2011. <<http://www.archiveglobal.org/haiti/downloads/I.7-Cost-of-Construction-Materials.pdf>>.

⁴⁹ Hulst, 17 Nov 2011

10 Appendix I: Work Breakdown Schedule

The work breakdown schedule for the entire design project is included on the following pages.

ID	Task Name	Duration	Start	Finish	Predecessor	Sep 11, '11							Sep 18, '11												
						M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S
1	Research	60 days	Tue 9/6/11	Mon 11/28/11																					
103	Librarian Consultation	1 day?	Mon 10/3/11	Mon 10/3/11																					
111	Final Report	40 days?	Wed 10/5/11	Tue 11/29/11																					
25	Project Website (Posted)	14 days	Fri 10/7/11	Wed 10/26/11																					
27	Preliminary Cost Estimate	13 days	Fri 10/7/11	Tue 10/25/11																					
40	Wentzheimer Meeting	153 days	Fri 10/7/11	Fri 5/4/12																					
17	Find funding for trip to Haiti	27 days?	Mon 10/10/11	Tue 11/15/11																					
18	Research funding	27 days?	Mon 10/10/11	Tue 11/15/11																					
19	Innotec Grant Application	2 days?	Thu 10/13/11	Fri 10/14/11																					
72	Team Meeting	146 days	Tue 10/11/11	Tue 5/1/12																					
2	Order Materials	6 days	Wed 10/12/11	Wed 10/19/11																					
114	Contact Potential Testing Sites	5 days?	Mon 10/17/11	Fri 10/21/11																					
26	Updated Project Poster	6 days	Wed 11/2/11	Wed 11/9/11																					
30	Preliminary Draft PPFS	6 days?	Tue 11/8/11	Tue 11/15/11																					
31	Introduction/Project Management	6 days?	Tue 11/8/11	Tue 11/15/11																					
32	Requirements	4 days?	Thu 11/10/11	Tue 11/15/11																					
33	Design Criteria	4 days?	Thu 11/10/11	Tue 11/15/11																					
34	Business Plan	4 days?	Thu 11/10/11	Tue 11/15/11																					
14	Business Plan	23 days?	Wed 11/9/11	Fri 12/9/11																					
16	Budget Planning	2 days?	Wed 11/9/11	Thu 11/10/11																					
15	Write Business Plan	19 days	Tue 11/15/11	Fri 12/9/11	16																				
38	Base Case Algor Analysis	10 days	Mon 11/14/11	Fri 11/25/11																					
39	Algor Base Case Analysis	10 days	Mon 11/14/11	Fri 11/25/11																					
104	Industrial Review (Larry Hulst) ???	1 day?	Tue 11/15/11	Tue 11/15/11																					
35	1st Draft PPFS	4 days	Wed 11/16/11	Mon 11/21/11																					
36	Edit PPFS	4 days	Wed 11/16/11	Mon 11/21/11	34																				
37	Submit and Post PPFS	1 day	Fri 11/18/11	Fri 11/18/11	30																				
20	Trip Planning	5 days?	Mon 11/21/11	Fri 11/25/11																					
22	Research plane tickets	5 days?	Mon 11/21/11	Fri 11/25/11																					
23	Hotel Reservations	4 days?	Tue 11/22/11	Fri 11/25/11																					
21	Purchase Plane Tickets	1 day?	Fri 11/25/11	Fri 11/25/11																					
105	Verbal Presentation II	1 day?	Mon 12/5/11	Mon 12/5/11																					
28	Preliminary Design Memo	3 days	Wed 12/7/11	Fri 12/9/11																					
24	Go to Haiti (?)	8 days	Wed 12/28/11	Sat 1/7/12	19																				
3	First Set of Panels	3 days?	Fri 2/10/12	Tue 2/14/12	2																				
4	Construct Mini-panel Frame	2 days	Fri 2/10/12	Mon 2/13/12																					
5	Pour Concrete for Mini-panel	1 day?	Tue 2/14/12	Tue 2/14/12	4																				
6	Test Mini-panels (Material Properties)	1.5 days	Wed 2/15/12	Thu 2/16/12	5																				
7	Analyze Test Results	3 days	Thu 2/16/12	Tue 2/21/12	6																				
8	Re-order Materials as needed	2 days	Wed 2/22/12	Thu 2/23/12	7																				
29	Develop Decision Matrix	3 days	Fri 2/24/12	Tue 2/28/12																					
9	Analyze Test Results 2	2 days	Tue 2/28/12	Wed 2/29/12	8																				
112	Test Panels (Structural Analysis)	1 day?	Tue 2/28/12	Tue 2/28/12																					
113	Analyze Test Results	3 days?	Wed 2/29/12	Fri 3/2/12	112																				
10	Second Set of Panels	5 days?	Sat 3/3/12	Thu 3/8/12																					
11	Construct Form for Full Panels	1 day?	Sat 3/3/12	Sat 3/3/12																					
12	Pour Concrete for Full Panels	5 days?	Sat 3/3/12	Thu 3/8/12																					
106	Complete design	15 days?	Mon 3/5/12	Thu 3/22/12																					
107	Structural details	14 days?	Mon 3/5/12	Wed 3/21/12																					
109	Architectural details	13 days?	Mon 3/5/12	Tue 3/20/12																					
110	Foundation Design	13 days?	Mon 3/5/12	Tue 3/20/12																					
108	Construct Full Size Panels	5 days?	Sat 3/17/12	Thu 3/22/12																					
13	Final Material Selection	4 days	Fri 3/9/12	Wed 3/14/12	12																				
115	Create Construction Manual	5 days?	Mon 3/19/12	Fri 3/23/12																					

Project: WBS.mpp
Date: Thu 12/8/11

Task

Split

Progress

Milestone

Summary

Project Summary

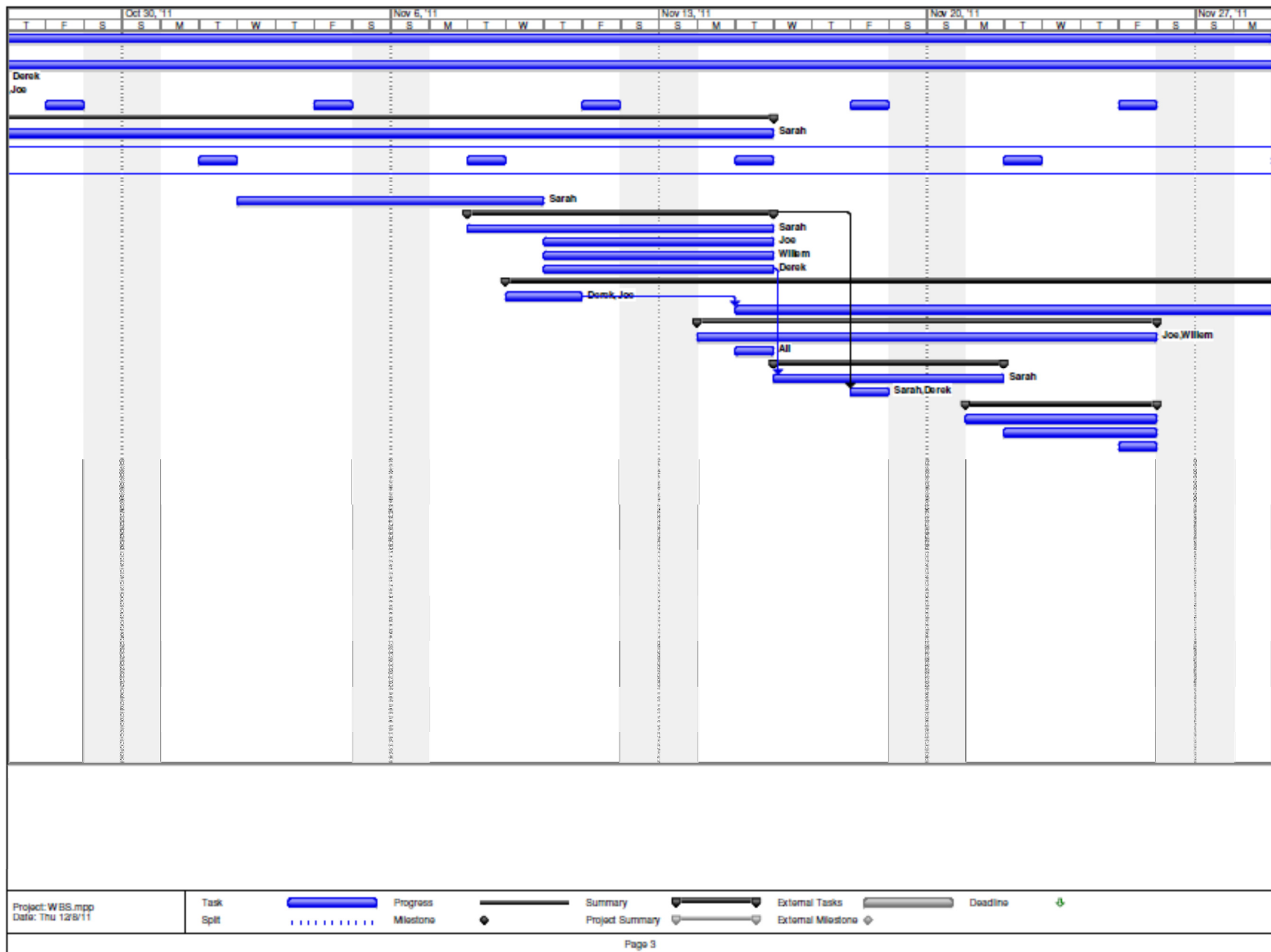
External Tasks

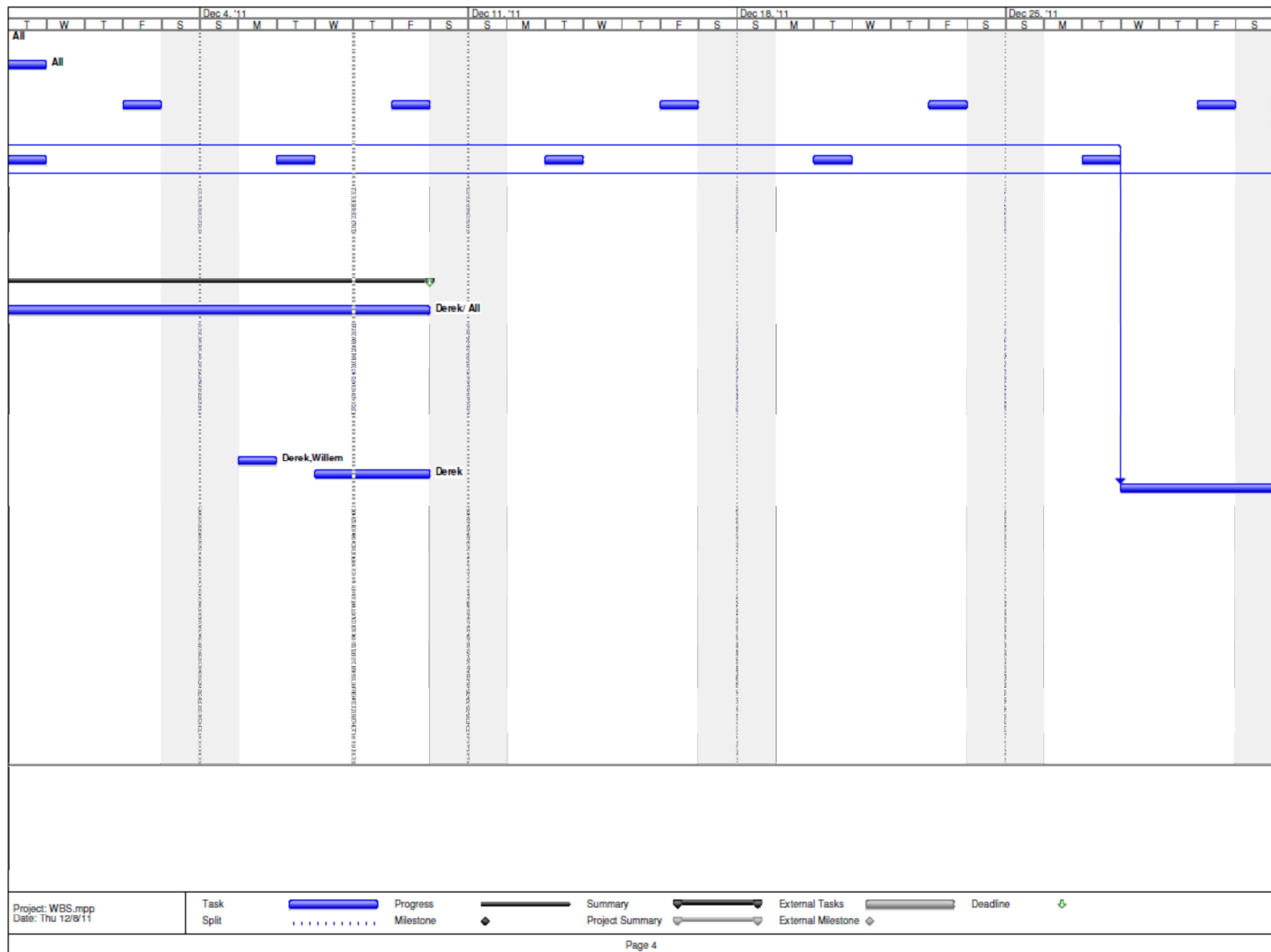
External Milestone

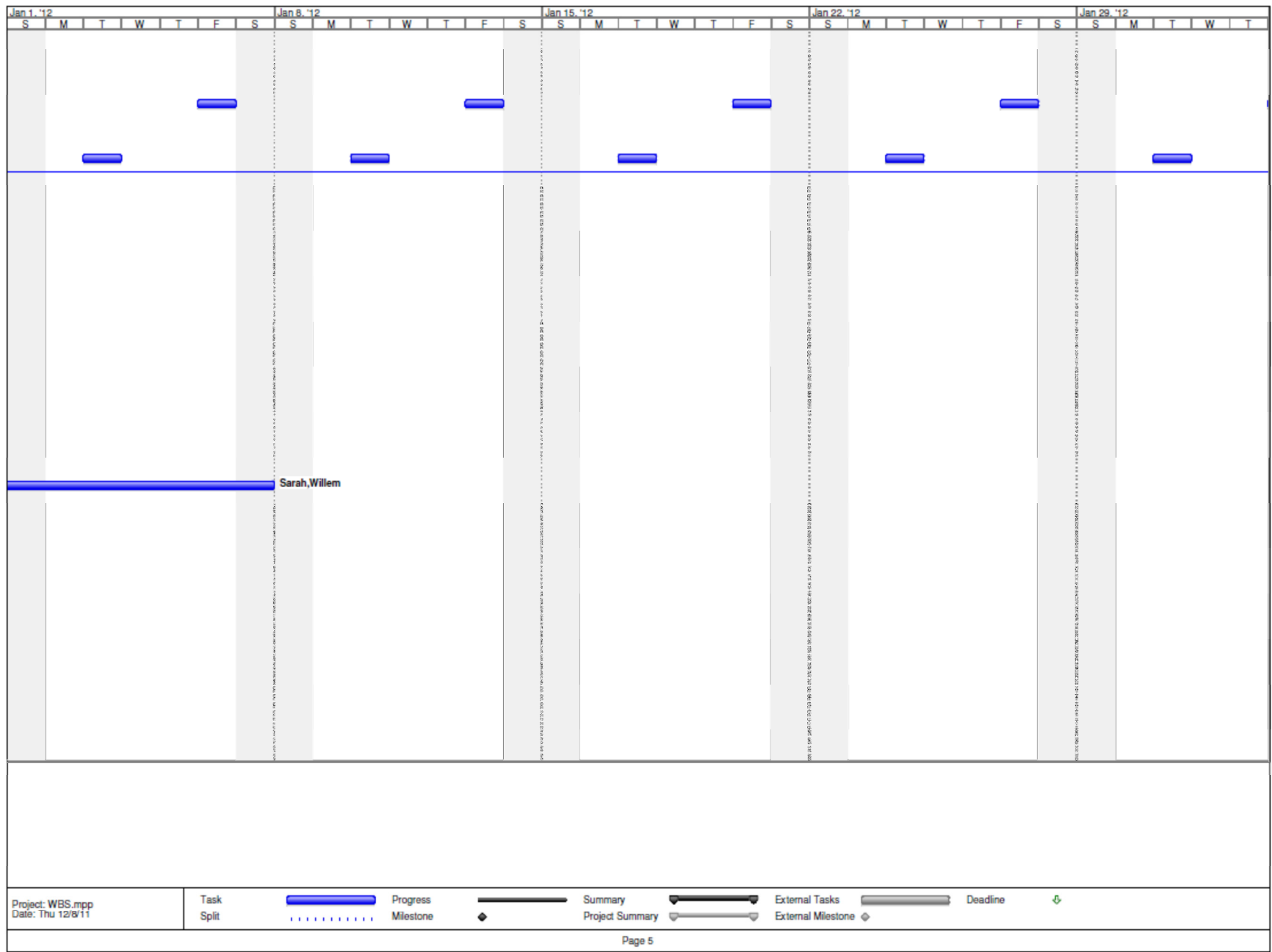
Deadline

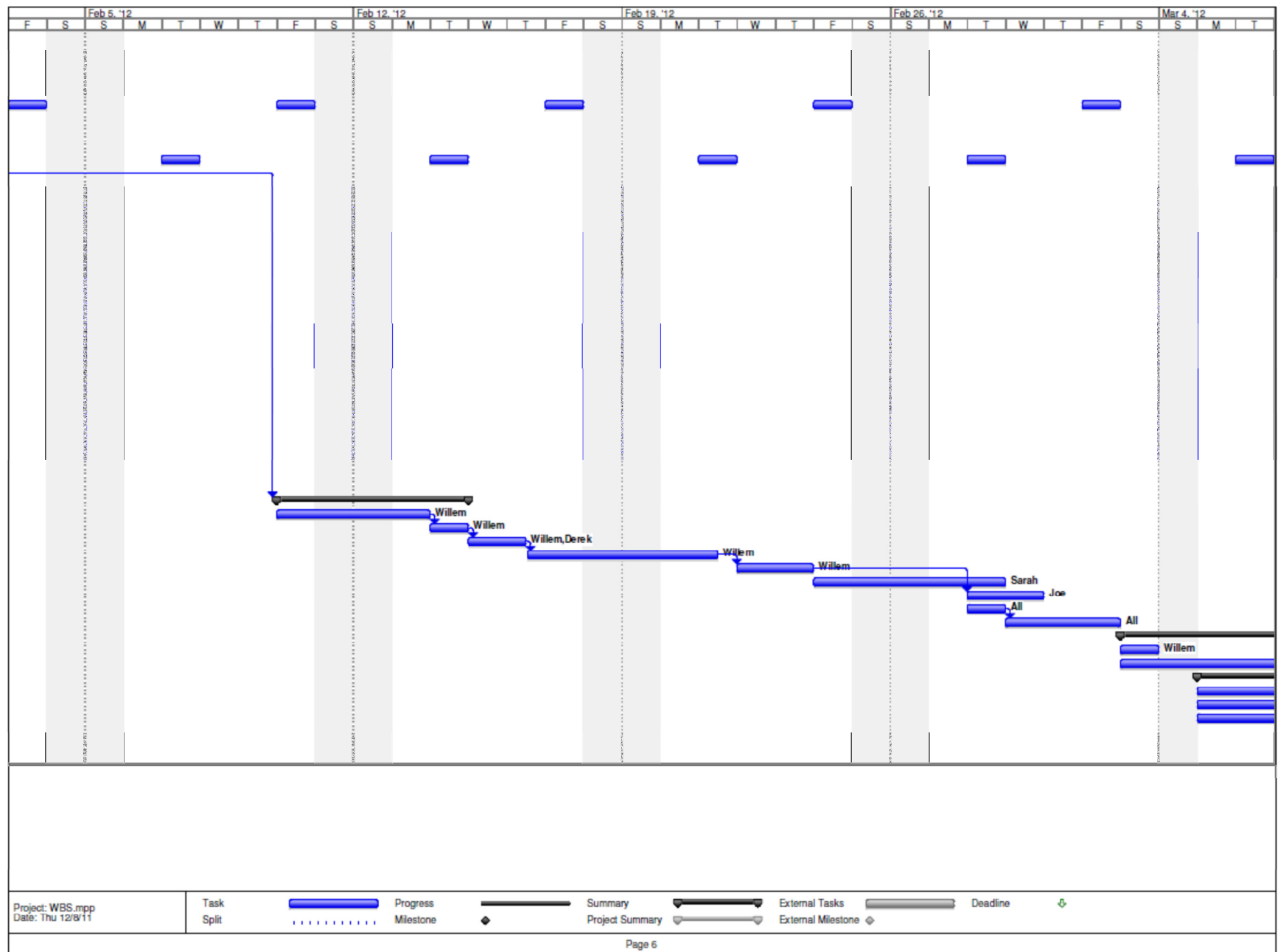
Page 1











11 Appendix II: Algor, Wind, and Seismic Calculations

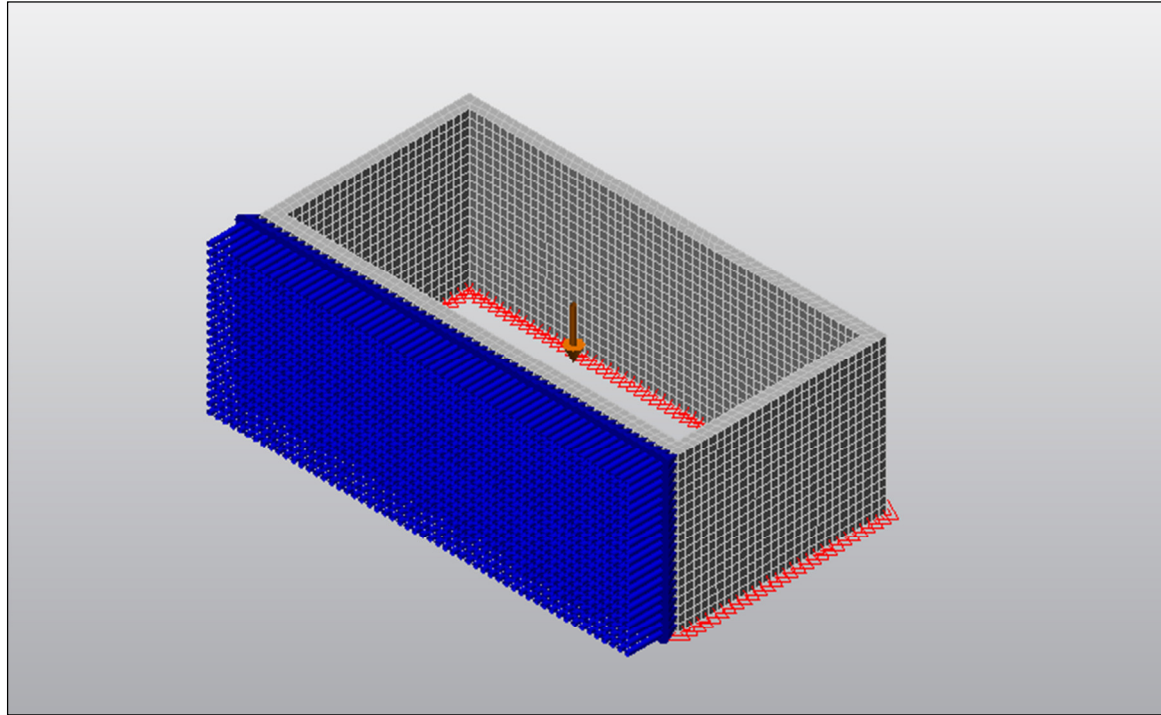


Figure 9: Base case model with wind load

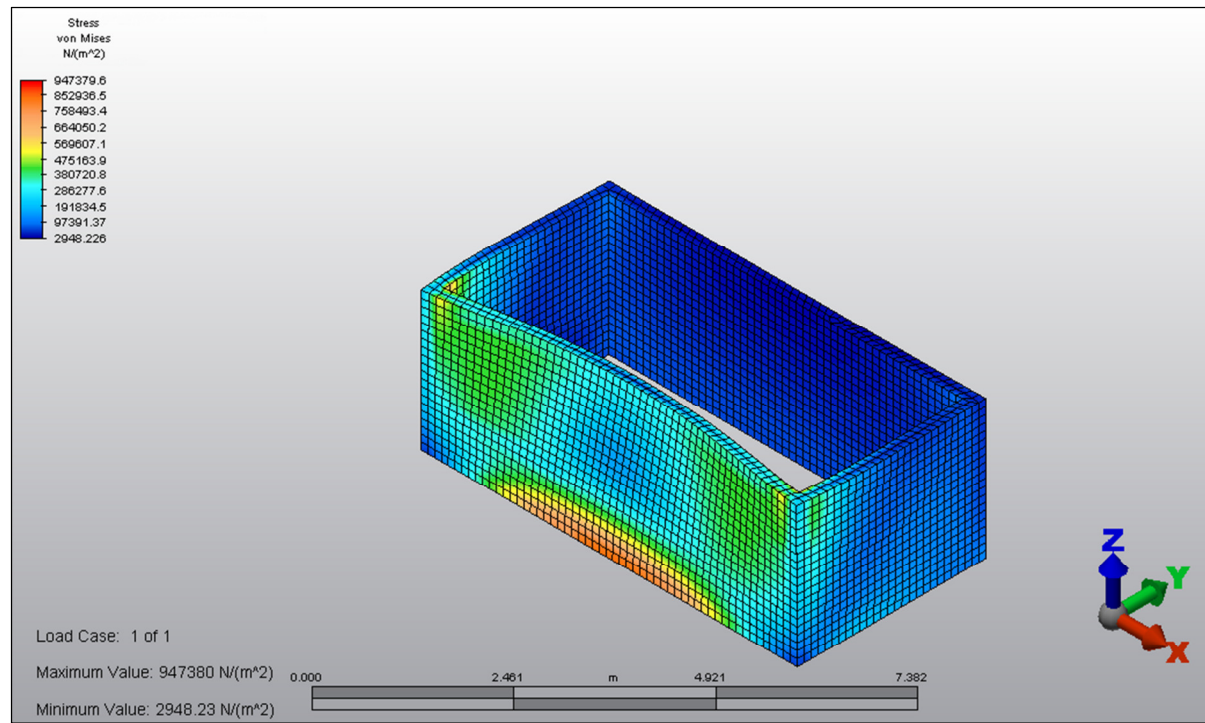


Figure 10: Deflected shape of base case with wind load

WIND LOAD CALCULATOR: ASCE 7-10			
DESIGNED BY SARAH FENNEMA			
CHECKED BY _____			

Figure 11: Inputs and outputs for calculation of wind loads

Table 13: Tables from the ASCE 7-10 code for calculating wind loads

TABLE 26.6-1: DIRECTIONALITY FACTOR

Structure Type	Directionality Factor, Kd
Buildings	
Main Wind Force Resisting System	0.85
Components and Cladding	0.85
Arched Roofs	0.85
Chimneys, Tanks, and Similar Structures	
Square	0.9
Hexagonal	0.95
Round	0.95

Solid Signs	0.85
Open Signs and Lattice Framework	0.85
Trussed Towers	
Triangular, square, rectangular	0.85
All other cross sections	0.95

TABLE 6-1: IMPORTANCE FACTOR

Category	Non-Hurricane Prone Regions	Hurricane Prone Regions
I	0.87	0.77
II	1	1
III	1.15	1.15
IV	1.15	1.15

Surface Factor	Roughness	Description
	B	Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or smaller
	C	Open terrain with scattered obstructions having heights generally less than 30 ft. This category includes flat open country and grasslands.
	D	Flat, unobstructed areas and water surfaces. This category includes smooth mud flats, salt flats, and unbroken ice.

Exposure Factor	Description
B	For buildings with a mean roof height of less than or equal to 30 ft, Exposure B shall apply where the ground surface roughness, as defined by Surface Roughness B, prevails in the upwind direction for a distance greater than 1500 ft. For buildings with a mean roof height greater than 30 ft, Exposure B shall apply where Surface Roughness B prevails in the upwind direction for a distance greater than 2600 ft or 20 times the length of the building, whichever is greater.
C	Exposure C shall apply for all cases where Exposure B or D do not apply.
D	Exposure D shall apply where the ground surface roughness, as defined by Surface Roughness D, prevails in the upwind direction for a distance greater than 5000 ft or 20 times the building height, whichever is greater. Exposure D shall also apply where the ground surface roughness immediately upwind of the site is B or C, and the site is within a distance of 600 ft or 20 times the building height, whichever is greater, from an Exposure D condition, as defined in the previous sentence.

Table 26.11-1

Classification	Enclosure Classification Definitions	Gcpi
Enclosed	A building that does not comply with the requirements for open or partially enclosed buildings	0.18
Partially Enclosed	A building that complies with both of the following conditions: 1) The total area of openings in a wall that receives positive external pressure exceeds the sum of the areas of openings in the balance of the building envelope by more than 10%. 2) The total area of openings in a wall that receives positive external pressure exceeds 4 ft ² or 1% of the area of that wall, whichever is smaller, and the percentage of openings in the balance of the building envelope does not exceed 20%.	0.55
Open	A building having each wall at least 80% open.	0

Table 14: Seismic load calculations for the base case model

SEISMIC LOAD CALCULATIONS					
CREATED BY SARAH FENNEMA					
CHECKED BY _____					
Parameter	Variable	Equation or Table Reference	Assumptions	Value	Units
Seismic Base Shear	V	$=C_s \cdot W$		103769.1	lb
Seismic Response Coefficient	C_s	$=S_{DS}/(R/I_e)$		13.12114	ft/s ²
Design Spectral Response Acceleration	S_{DS}	$=2/3 \cdot S_{MS}$		19.68171	ft/s ²
Spectral Response Acceleration	S_{MS}	$=F_A \cdot S_S$		29.52257	ft/s ²
Mapped Short Period Spectral Response Acceleration	S_S	USGS Website	$=83.35\% \cdot \text{gravitational constant}$	26.8387	ft/s ²
Site Coefficients	F_a	Table 11.4-1	Site Class D	1.1	
Response Modification Factor	R	Table 12.2-1	Ordinary Plain Concrete Shear Walls	1.5	
Importance Factor	I_e	Table 1.5-2	Risk Category II Building	1	
Seismic Weight of Building	W	$=2 \cdot W_{w1} + 2 \cdot W_{w2} + W_{roof}$		7908.542	lb
Type 1 Wall Weight	W_{w1}	$=W_c \cdot L \cdot w_{bl} / 12 \cdot H$		1860.833	lb
Type 2 Wall Weight	W_{w2}	$=W_c \cdot w \cdot w_{bl} / 12 \cdot H$		930.4167	lb
Weight of Roof	W_{roof}	$=W_c \cdot w \cdot L \cdot w_{bl} / 12$		2326.042	lb
Weight of Concrete	W_c		Assuming 1/8 Weight of Normal Concrete	18.125	lb/ft ³
Length of Building	L			20	ft
Width of Building	w			10	ft
Block width	w_{bl}			7.7	in
Height of Building	H			8	ft

Table 15: Seismic load calculation for the base case model (Note: F_x is the force seen by each level of blocks in the building model)

Parameter	Variable	Equation or Table Reference	Value	Units		Level Number	Elevation	C_vx	F_x	F_x/node
Total Height	H		8 ft			1	0.4	1.00	103769.1	1853.02
Level Separation	h_i		0.4 ft			2	0.8	0.50	51884.55	926.5098
Number of Levels	n	$=H/h_i$	20			3	1.2	0.33	34589.7	617.6732
Weight of Each Level	w_i	$=W_c \cdot h_i \cdot w_{bl} \cdot L + W_c \cdot h_i \cdot w_{bl} \cdot w$	139.5625	lb		4	1.6	0.25	25942.27	463.2549
		$=w_i \cdot h_i$	55.825	lb*ft		5	2	0.20	20753.82	370.6039
Seismic Base Shear	V		103769.1	lb		6	2.4	0.17	17294.85	308.8366
						7	2.8	0.14	14824.16	264.7171
						8	3.2	0.13	12971.14	231.6275
						9	3.6	0.11	11529.9	205.8911
						10	4	0.10	10376.91	185.302
						11	4.4	0.09	9433.555	168.4563
						12	4.8	0.08	8647.425	154.4183
						13	5.2	0.08	7982.238	142.54
						14	5.6	0.07	7412.079	132.3585
						15	6	0.07	6917.94	123.5346
						16	6.4	0.06	6485.569	115.8137
						17	6.8	0.06	6104.065	109.0012
						18	7.2	0.06	5764.95	102.9455
						19	7.6	0.05	5461.532	97.52735
						20	8	0.05	5188.455	92.65098

12 Appendix III: Concrete Material Properties for Algor

Equation for the Modulus of Elasticity & Shear Modulus

$$\nu := 0.15$$

Poisson's Ratio

$$w_c := 145$$

w.c is the weight of concrete in pounds/cubic ft

$$f_c := 4000$$

f.c is the compressive strength of concrete in pounds/ square in

$$E_{cinch} := 33 \cdot (w_c)^{1.5} \cdot (f_c)^{-5}$$

E.cinch is the Modulus of Elasticity in pounds/ square in

$$E_{cinch} = 3.644 \times 10^6$$

$$E_{cfoot} := E_{cinch} \cdot 144$$

E.cfoot is the Modulus of Elasticity in pounds/ square ft

$$E_{cfoot} = 5.248 \times 10^8$$

$$G_c := \frac{E_{cfoot}}{2(1 + \nu)}$$

G.c is the Shear Modulus in pounds/ square ft

$$G_c = 2.282 \times 10^8$$

Values for Weight and Compressive Strength of Concrete in Haiti

$$w_{haiti} := \frac{145}{8}$$

w.haiti is the weight of concrete in pounds/cubic ft

$$f_{haiti} := 1300$$

f.haiti is the compressive strength of concrete in Haiti in pounds/ square in

$$E_{haitiinch} := 33 \cdot (w_{haiti})^{1.5} \cdot (f_{haiti})^{-5}$$

E.haitiinch is the Modulus of Elasticity for concrete in Haiti in pounds/square in

$$E_{haitiinch} = 9.181 \times 10^4$$

$$E_{haitifoot} := E_{haitiinch} \cdot 144$$

E.haitifoot is the Modulus of Elasticity of Haitian concrete in pounds/square ft

$$E_{haitifoot} = 1.322 \times 10^7$$

Values of shear modulus of elasticity for Haiti

$$\nu := 0.15$$

$$G_{\text{haiti}} := \frac{E_{\text{haiti}}}{2(1 + \nu)}$$

G.haiti is the Shear Modulus of Haitian Concrete
in pounds/square ft

$$G_{\text{haiti}} = 5.748 \times 10^6$$

Moment of Inertia of a Concrete Block

$$l_o := 16\text{in} \quad \text{outer length}$$

$$w_o := 8\text{in} \quad \text{outer width}$$

$$l_i := 4\text{in} \quad \text{inner length of one hole}$$

$$w_i := 4\text{in} \quad \text{inner width of one hole}$$

$$I := \frac{l_o \cdot w_o^3}{12} - 2 \cdot \frac{l_i \cdot w_i^3}{12} = 640 \cdot \text{in}^4$$

moment of inertia of concrete block with two holes

$$t := \left(\frac{12 \cdot I}{l_o} \right)^{\frac{1}{3}} = 7.83 \cdot \text{in}$$

thickness of solid block with same moment of inertia

Concrete Mix

$$\rho_{\text{cementperbag}} := 94 \frac{\text{lb}}{\text{ft}^3}$$

$$V_{\text{panel}} := [(1.5 \cdot 30 \cdot 98.4) \text{in}^3 - (1.5 \cdot 26 \cdot 94.4) \text{in}^3] + (1 \cdot 98.4 \cdot 30) \text{in}^3 = 0.061 \cdot \text{m}^3 \quad \text{Panel Volume}$$

$$V_{\text{house}} := V_{\text{panel}} \cdot 30 = 1.818 \cdot \text{m}^3 \quad \text{Volume of 30 Panels}$$

$$V_{\text{cement}} := V_{\text{house}} \cdot 0.4 = 0.727 \cdot \text{m}^3 \quad \text{Cement Volume}$$

$$m_{\text{cement}} := V_{\text{cement}} \cdot \rho_{\text{cementperbag}} \quad \text{Volume from 1 Pound of Cement}$$

$$m_{\text{cement}} = 1.095 \times 10^3 \text{ kg} \quad \text{Mass of Cement Required}$$

$$\text{bags} := \frac{m_{\text{cement}}}{42.5 \text{ kg}} = 25.767 \quad \text{Bags Required}$$

$$\text{cost} := 7.50 \frac{\text{Dollars}}{\text{Bag}}$$

$$\text{bags} \cdot \text{cost} = 193 \text{ Dollars} \quad \text{Cement Cost}$$

$$\frac{42.5 \text{ kg}}{V_{\text{panel}} \cdot 0.4 \cdot \rho_{\text{cementperbag}}} = 1.164 \frac{\text{Panels}}{\text{Bag}}$$

$$V_{\text{sand}} := V_{\text{cement}}$$

$$\text{sand} := \frac{16.25}{\text{m}^3} \text{ Dollars}$$

$$V_{\text{sand}} \cdot \text{sand} = 12 \text{ Dollars} \quad \text{Price of Sand}$$

Labor Costs:

Unskilled Labor:

Unskilled Labor Supervisor:

$$\text{wage}_{\text{unsk}} := \frac{2}{\text{day}} \text{ Dollars}$$

$$\text{wage}_{\text{ULS}} := \frac{8}{\text{day}} \text{ Dollars}$$

$$\text{time}_{\text{const}} := 300 \text{ hr}$$

$$\text{wage} := (\text{wage}_{\text{unsk}} \cdot 4 + \text{wage}_{\text{ULS}}) \cdot \text{time}_{\text{const}} \quad \text{wage} = 200 \text{ Dollars}$$